PROPERTIES OF ENGINEERING MATERIALS FOR USE IN ROTATING MACHINERY AT CRYOGENIC TEMPERATURES

pt.1

William Martin Dubbs

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by

WILLIAM MARTIN DUBBS, JR.

LIEUTENANT, UNITED STATES NAVY

B.S., United States Naval Academy

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William Martin Dubbs, Jr.

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ABSTRACT

The properties of engineering materials which are useful to the designer of superconducting electrical machinery are discussed. Of all possible properties of a material, the ones most necessary to rotating machinery design are listed and defined. This is followed by a description of those organizations which both compile and store property data along with a description of those journals and books which contain property data.

Seventy-six tables of numerical data with all the data referenced to their source are provided along with those reasonable conclusions which can be drawn from the data regarding how materials behave from room temperature to cryogenic temperatures. Comments are also made on those areas where further research is needed. This is followed by a bibliography of references for those who seek further detail.

The data indicates that many materials have adequate cryogenic mechanical properties, particularly ductility, for use in superconducting electric machinery. Given a particular machine part with its design constraints, the designer must trade off the beneficial or detrimental effects of all the properties tabulated to find a material tailored to his needs.

Thesis Supervisor: P. Thullen

Title: Associate Professor of Mechanical Engineering

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GLOSSARY OF SYMBOLS

SYMBOL	MEANING
σ	generalized stress, electrical conductivity
ε	generalized strain
σ_{yield}	yield strength
σ_{uts}	ultimate tensile strength
E	Young's Modulus
ν	Poisson's ratio
G	Modulus of Rigidity
τ_{yield}	shear yield strength
τ_{uts}	shear ultimate strength
K_c	critical stress intensity factor (plane stress)
K_{Ic}	critical stress intensity factor (plane strain)
F_n	fatigue strength for failure at n cycles
q	notch sensitivity index
k_f	fatigue strength reduction factor
k_t	theoretical stress concentration factor, temperature integral of thermal conductivity
k	thermal conductivity
c_p	specific heat at constant pressure
c_v	specific heat at constant volume
α	linear thermal expansion coefficient
ρ	density, electrical resistivity
ν	specific volume

μ	magnetic permeability
μ_0	magnetic permeability of vacuum
μ_r	relative magnetic permeability
B	magnetic flux density
H	magnetic field intensity
R	stress ratio

CHAPTER 1

INTRODUCTION

In the past few years, the interest in electrical generators and motors which use the principle of superconductivity has increased greatly. This interest has been brought about by the fact that very large turbogenerators have just about reached the maximum feasible size for today's engineering materials and technology.[1,2,3] As the nation's demand for electric power keeps increasing, the power industry's desire for generators of larger output will also increase, so something of a stalemate has been reached with conventional generators. It is an established fact that superconducting generators are physically a great deal smaller than their conventional counterparts for the same power output,[1,4,5,6] thus making them very attractive.

Another area of interest in superconducting generators and motors lies with the Department of Defense, particularly the United States Navy. Electric propulsion has been used on submarines for years, and on surface ships generally as a last resort in times of national emergency when every propulsion plant was needed, but in both cases at a great sacrifice in added weight for the horsepower achieved. However, in peacetime when economic and performance characteristics dominate electric propulsion is at most used as an emergency propulsion system. The advent of superconducting generators and motors, because of their high power outputs for their low weights may well alter the importance of this method of ship propulsion.

The technical feasibility of superconducting generators and motors has been demonstrated recently by the successful construction and operation of several such units, and the interest in their further refinement has intensified. The Cryogenic Engineering Laboratory at M.I.T. has recently made and operated a 2 MVA synchronous generator with a rotor which contains a superconducting field winding. Numerous engineering problems had to be solved in taking this generator from concepts and theory to an actual hardware device, not the least of which was the choice of adequate construction materials, particularly for the rotor. Some of the components of the generator are subjected to a variety of loads while being kept at cryogenic temperatures during operation.

Since the main purpose of the M.I.T. Cryogenic Engineering Laboratory staff in building this generator was to demonstrate the feasibility of such a machine, adequate but not necessarily the optimum materials were used for its construction. Now that the feasibility has been established, there is a need to be able to more carefully select the construction materials. The materials of the existing generator, while adequate for the short term, may or may not be adequate for a machine designed with a 30 year service life.

CHAPTER 2

SELECTION OF APPLICABLE PROPERTIES

2.0 Background

The logical first step in a project of this type is to determine which properties, of all possible properties of a given engineering material, are the most applicable to the design of superconducting electrical machinery. While relatively few of the structural components of a superconducting generator or motor are maintained during operation at liquid helium temperatures, many components are kept at a steady-state temperature well below those found in a conventional generator. Hence, some of the properties and much of the data found in the usual handbooks are not very useful because the temperature ranges provided are not low enough.

The properties which have been determined to be important to superconducting electrical machinery design are not substantially different from those a conventional generator design would require. However, this list encompasses more properties than are usually considered to prevent overlooking any low temperature effects which could be detrimental to the ultimate design.

To provide for ease in the use of this document, a list summarizing the selected material properties will precede a definition and reason for selection of each property.

2.1 Summary of Applicable Properties

Mechanical Properties

Tensile Properties

- Proportional (or elastic) limit
- Yield strength (or proof stress)
- Ultimate tensile strength
- Young's Modulus (Modulus of Elasticity)
- Poisson's ratio
- Percentage elongation
- Percentage reduction in area

Torsional Properties

- Modulus of Rigidity (Shear Modulus of Elasticity)
- Shear yield strength
- Shear ultimate tensile strength

Property of Notch Toughness

Fatigue Properties

- S-N curve
- Endurance limit
- Fatigue strength
- Notch sensitivity index

Thermophysical Properties

Thermal Conductivity

Specific Heat

Linear Thermal Expansion Coefficient

Density (of Specific Volume)

Electrical Properties

Electrical Resistivity (or Conductivity)

Magnetic Properties

Permeability

Hysteresis Curves

Normal Magnetization Curves

Saturation Magnetic Field Intensity

2.2 Property Definition and Usage

2.2.1 Mechanical Properties

2.2.1.1 Tensile Properties[7,8]

These properties are the significant results obtained with a stress-strain curve derived from the usual tensile specimen testing. For reference refer to Figure 2.1.

2.2.1.1.1 Proportional (or Elastic) Limit

This is defined as the maximum stress to which a specimen can be subjected and still exhibit elastic behavior. It is therefore the stress at which the stress-strain curve deviates from a straight line. This is stress point A on Figure 2.1.

2.2.1.1.2 Yield Strength (or Proof Stress)

This is defined as the stress at which the specimen undergoes a marked elongation without an increase in load. Since this definition is somewhat arbitrary, there are two generally accepted ways to determine yield stress.

One method is to draw a parallel offset from the straight line portion of the stress-strain curve and where this offset intersects the stress-strain curve is the yield strength. The amount of offset is arbitrary and is expressed as strain in percentage. Point B in Figure 2.1 is one possible offset with a corresponding yield strength

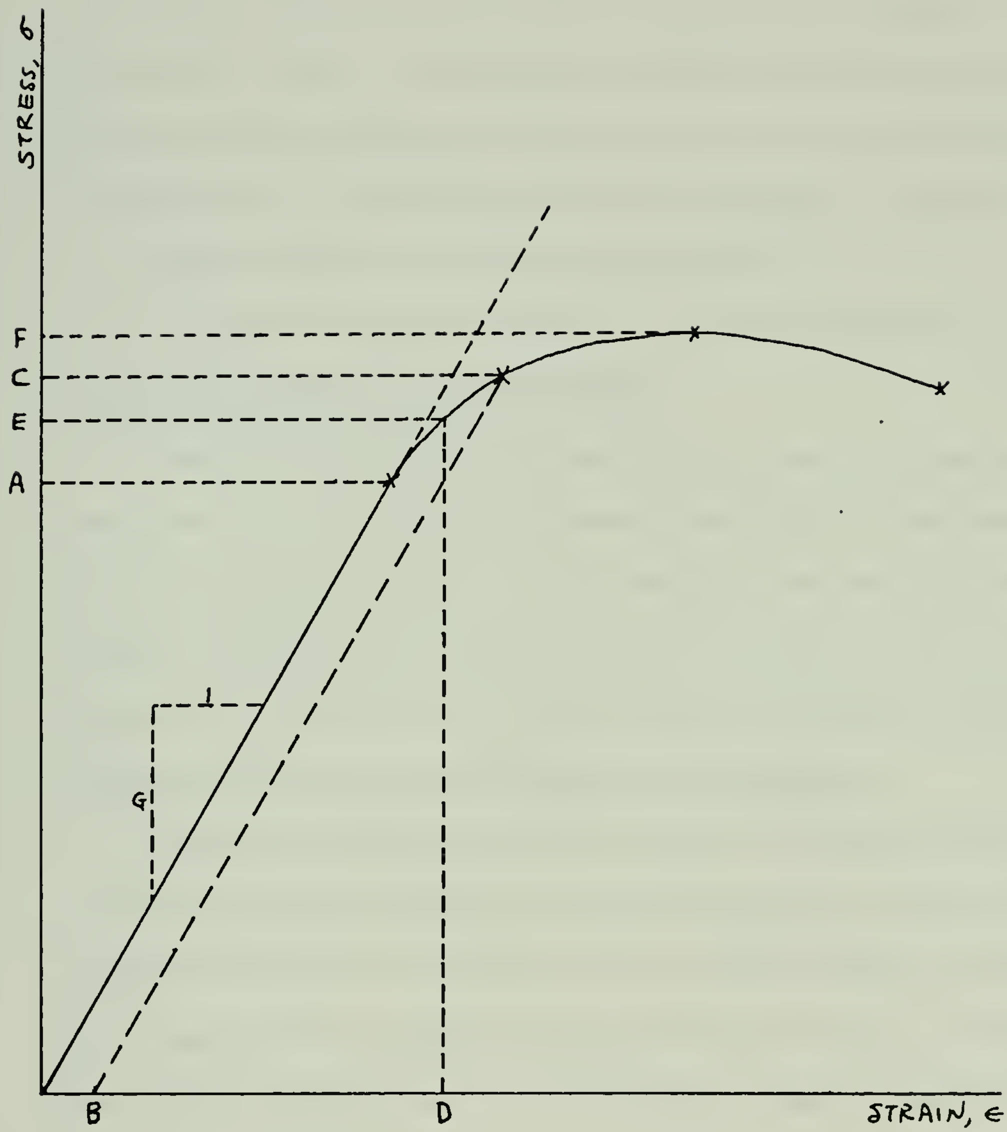


Figure 2.1 Typical Stress-Strain Curve

represented by point C. When using this method the yield strength is called the yield strength at an offset of B per cent.

The second method is to assume an extension such as point D in Figure 2.1 where this extension is the strain expressed as a percentage. Where a vertical line drawn from this assumed extension intersects the stress-strain curve gives the yield strength (point E on Figure 2.1). When using this method the yield strength is called the yield strength for a D per cent extension.

In either case yield strength is usually written as σ_{yield}.

2.2.1.1.3 Ultimate Tensile Strength

This is defined as the maximum tensile load the specimen is subjected to divided by the cross-sectional area of the specimen before straining occurred. It is therefore the stress at the highest point on the stress-strain curve, which is point F in Figure 2.1. The ultimate tensile strength is usually written as σ_{uts}.

2.2.1.1.4 Young's Modulus (Modulus of Elasticity)

For the portion of the stress-strain curve where Hooke's Law is valid, in other words where the stress-strain curve can be approximated well by a straight line, Young's Modulus is defined as the slope of this straight line portion of the curve. On Figure 2.1 this slope is represented by the value G. Young's Modulus is usually written as the letter E.

2.2.1.1.5 Poisson's Ratio

This is defined as the ratio of the unit transverse contraction to the unit axial elongation of the tensile specimen and is only valid in the elastic range of the material. Poisson's ratio is

usually written as the letter ν.

2.2.1.1.6 Percentage Elongation

This is a measure of the extension of a tensile specimen in the vicinity of the fracture and is defined as the ratio of the specimen length at fracture to the original guage length of the specimen expressed as a percentage.

2.2.1.1.7 Percentage Reduction in Area

This is defined as the ratio of the smallest cross-sectional area at the point of rupture to the original cross-sectional area of the specimen expressed as a percentage.

2.2.1.1.8 Usefulness of Tensile Properties

All of these tensile properties are used at one time or another in standard stress analysis of any structure. In particular, with rotating electrical machinery, there are a multiutde of tensile loads which various components see such as pre-stressing of certain components, centrifugal loads, surface tensile loads brought about by bending, etc. All of the tensile properties chosen with the exceptions of Poisson's ratio, percentage elongation and percentage reduction in area come directly from a stress-strain curve, however, these three are easily determined at the same time as the curve data is being generated and in the literature often accompany the curve.

Percentage elongation and percentage reduction in area are used in design as measures of the ductility of the material in question. Materials which are considered brittle have low values of these properties. The dividing line between brittleness and

ductility is an arbitrary one with percentage reduction in area being used more commonly as a measure of ductility.[11] In general, a material with less than a few per cent reduction in area is considered brittle.[12]

2.2.1.2 Torsional Properties[7,9,10]

These properties are obtained from a shear stress-shear strain curve produced from the standard torsion testing procedures. In form this curve is very similar to the tensile stress-strain curve of Figure 2.1. Therefore, the points on this figure will be used for reference.

2.2.1.2.1 Modulus of Rigidity (Shear Modulus of Elasticity)

For the portion of the shear stress-shear strain curve where the curve is closely approximated by a straight line and the material behaves elastically, the Modulus of Rigidity is defined as the slope of the curve. On Figure 2.1 this slope is represented by G. The Modulus of Rigidity is usually written as the letter G.

2.2.1.2.2 Shear Yield Strength

As with the tensile yield strength this is defined as the shear stress at which the specimen undergoes a marked deformation without an increase in torque. The method used to determine this value is the percentage offset method described in Section 2.2.1.A.2. Hence, from Figure 2.1, a material has a shear yield strength of E at an offset of B per cent. Shear yield strength is usually written as τ_{yield}.

2.2.1.2.3 Shear Ultimate Strength

This is defined as the maximum torsional load the specimen is

subjected to divided by the cross-sectional area of the specimen before shear straining occurred. It is therefore the value of shear stress at the highest point on the shear stress-shear strain curve; point F in Figure 2.1. This is usually written as τ_{uts}.

2.2.1.2.4 Usefulness of Torsional Properties

These properties are useful to the electrical machinery designer when he is concerned with stress analysis of those components subjected to torques, principally the rotor shaft and end bell assemblies subjected to inertial torques.

2.2.1.3 Property of Notch Toughness[9,12]

This material property is given a variety of names in the literature. The various names are:

notch toughness

toughness

notch sensitivity

impact strength

fracture toughness

Basically notch toughness is a measure of the resistance of a material to the emanation of brittle fracture from a crack in a notch of a specimen which is subjected to some form of load. This is an extremely temperature dependent property in that at either a specific temperature or over a temperature range, the material will shift from acting as a ductile material to acting as a brittle material in the area of a pre-placed notch or discontinuity.

There are a multitude of testing procedures used to evaluate this property with an equally diverse number of test results. The

more common tests are:

Charpy Impact Test

Drop Weight Test

Dynamic Tear Test

The results of these and the less frequently used testing procedures are generally a list of key temperatures at which specified phenomena are observed.

In addition to the test results themselves, fracture mechanics theory has been combined with certain experimental results to yield yet another method of presenting notch toughness data in such terms as critical stress intensity factor in plane stress (K_c) and critical stress intensity factor in plane strain (K_{Ic}).

2.2.1.3.1 Usefulness of Notch Toughness

Given that there are so many ways to quantify and present notch toughness data, each dependent on the method of testing, the superconducting electrical machinery designer must use his own judgment of the data available to him by having a prior knowledge of how the data was obtained and which components of his machine will have notches or other discontinuities where fractures may initiate. This is not meant to downgrade the value of knowing notch toughness to the designer, however, even with what he considers useful data, his use of this information will be largely qualitative in nature and based on his previous experience.

2.2.1.4 Fatigue Properties[9,12,13]

As a result of the differences in material behavior for different stress loads and cycle rates, fatigue data is generally

divided into two major categories. High cycle-low stress fatigue is that where the stress levels are within the elastic range of the material; and low cycle-high stress fatigue involves plastic deformation during stress periods. The division between these two categories is somewhat arbitrarily taken as 10^5 cycles to failure.[12]

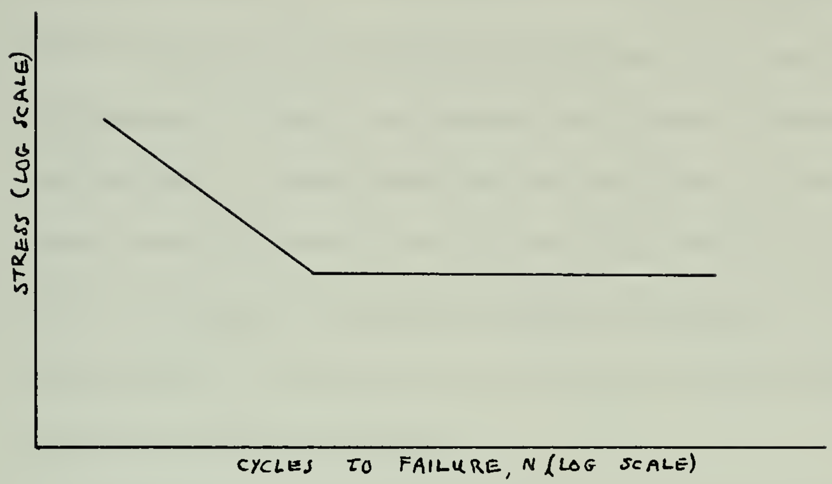
The user of fatigue data must know what type of loading was used in generating the data. Generally, there are three basic methods of loading: flexure, torsion and longitudinal stress. Within each of these basic load types the loading may have been alternating, implying a complete reversal of maximum load on each cycle, or pulsating, implying loading always in the same direction with a return to zero on each cycle.

2.2.1.4.1 S-N Curve

This curve can be given one of two ways depending on whether high cycle-low stress or low cycle-high stress fatigue is involved. High cycle-low stress fatigue data is usually presented on a maximum nominal stress(S) to number of cycles to failure (N) curve, A characteristic of this type of curve is that for low enough stress, the curve will level off to a horizontal line. This curve is often plotted on a log-log scale. See Figure 2.2. Low cycle-high stress fatigue data is usually presented on a total strain (S) to number of cycles to failure (N) curve. This curve is usually also presented with a log-log scale, however, generally does not level off at any low strain value. See Figure 2.2.

2.2.1.4.2 Endurance Limit

This property is valid only for high cycle-low stress fatigue



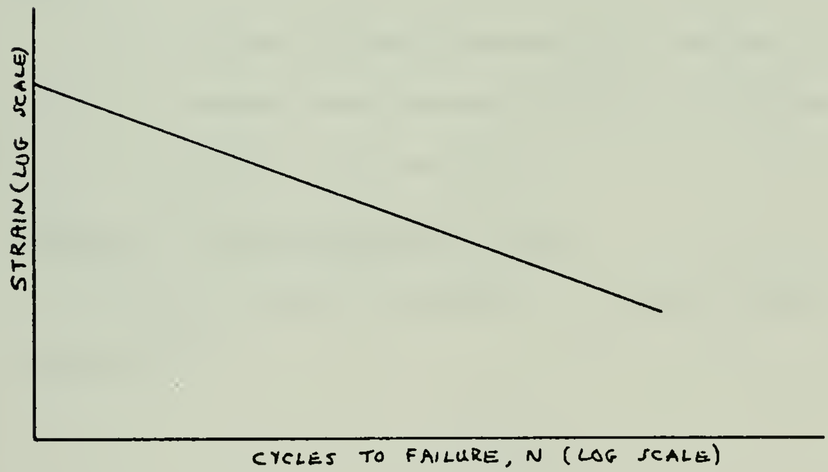


Figure 2.2   Typical S-N Curves(12)

data and comes directly from the maximum stress to number of cycles to failure curve. It is defined as the stress at which the curve becomes substantially horizontal and hence, at any stress lower than the endurance limit, the material will have a supposed infinite fatigue life. Aside from the arbitrariness of exactly where the curve goes horizontal, not all materials exhibit an endurance limit, although all stress to number of cycles to failure curves become almost horizontal at a high enough number of cycles.[12]

2.2.1.4.3 Fatigue Strength

This is a property derived from whichever S-N curve is appropriate. It is defined as:[12]

$$F_n = S(N/n)^k$$

where

F_n = fatigue strength computed for failure at n cycles

S = stress which produced failure in N cycles

k = slope of the S-N curve

2.2.1.4.4 Notch Sensitivity Index

This is a derived property of a material which comes from the formula:[12]

$$q = \frac{k_f - 1}{k_t - 1}$$

where q is the notch sensitivity index, k_f, is the fatigue strength reduction factor and k_t is the theoretical stress concentration factor.

The theoretical stress concentration factor is derived with assumed geometry and assumed elastic behavior of the material.

Fatigue strength reduction factors are derived with a combination of testing and theory for particular stress concentration factors with particular materials. The form of presentation of all these factors may vary widely depending on the reference used.

2.2.1.4.5 Usefulness of Fatigue Properties

At the present time there are no generally accepted methodical procedures for incorporating fatigue property data into the electrical machine design process. At very best the designer would be able to calculate the fatigue loading of each individual component and then find S-N curve data for the same types of loading. However, more than likely he will not find the exact S-N curve and will have to use considerable judgment in the selection of a material. S-N curves probably give the most complete picture of the fatigue behavior of a material, subject to the constraints of the testing procedure. However, a knowledge of the endurance limit and fatigue strength allow a relative ranking of the different materials to be made. With a knowledge of these properties and some prior experience of which materials have withstood the test of time, a selection can be made. Notch sensitivity index data creates a further refinement in the selection process since if the exact geometry of the machine component is known, then the situation may exist where a less expensive material may be adequate because the notch sensitivity of the material overrides higher strength considerations.

2.2.2 Thermophysical Properties

2.2.2.1 Thermal Conductivity[14,15,16,17]

This property is an index of the ease with which heat energy

is transferred through the material by conduction. Since thermal conductivity is such a strongly temperature dependent property, it is presented in one of two ways in the literature. Either it is given as values of thermal conductivity, k, versus temperature or as values of the temperature integral of thermal conductivity from 0°K to each higher temperature.

2.2.2.1.1 Usefulness of Thermal Conductivity

This property is used very commonly in heat transfer calculations and by itself provides an excellent measure for the ranking of many materials as to their quality as conductors or insulators of heat.

2.2.2.2 Specific Heat[18,19,20]

This is a property used to describe the rate of change of the internal energy or enthalpy of a material with a change in temperature. Specific heat may be given as c_p, specific heat at constant pressure, or c_v, specific heat at constant volume. For solid materials such as would be considered for electrical generator design specific heat at constant pressure is the most important property to know since c_v for solids is purely a derived property based on the experimentally obtained value of c_p through such approximations as the Nerst-Lindemann equation or is obtained from other theoretical methods such as the Debye equations.[18] Generally, at very low temperatures, the numerical difference between c_p and c_v is negligible small with this difference increasing with increasing temperature. Specific heat at constant pressure is an extremely temperature dependent property which by definition goes to zero at 0°K.

2.2.2.2.1 Usefulness of Specific Heat

Specific heat, as with thermal conductivity, is used quite frequently in standard heat transfer and thermodynamic calculations.

2.2.2.3 Linear Thermal Expansion Coefficient[8,18]

This is defined as the unit change in length of a bar of material per unit original length per degree change in temperature. Since the linear thermal expansion coefficient is such a strongly temperature dependent property, it is presented in one of two ways in the literature. Either it is given as values of the expansion coefficient, α, versus temperature or as values of the temperature integral of the expansion coefficient from 0°K to each higher temperature.

2.2.2.3.1 Usefulness of Linear Thermal expansion Coefficient

This property is useful in the calculations concerning component clearances and tolerances, particularly for the differences in these clearances when the machine is idle and the machine is running.

2.2.2.4 Density (Specific Volume)

Density is defined as the mass per unit volume of a material. Its reciprocal, called specific volume, is sometimes given in data tables. Density is usually written as ρ and specific volume is usually written as υ.

2.2.2.4.1 Usefulness of Density (Specific Volume)

These properties are used in all weight calculations and, given the inherent weight savings of superconducting electrical machines over conventional machines, become very important.

2.2.3 Electrical Properties

2.2.3.1 Electrical Resistivity (Conductivity)[21,22]

Electrical resistivity is defined as the resistance in ohms of a volume of material of unit cross-section and unit length. Electrical conductivity is its reciprocal. Electrical resistivity is usually written as ρ while electrical conductivity is usually written as σ.

2.2.3.1.1 Usefulness of Electrical Resistivity (Conductivity)

Since electrical losses such as current-conduction losses, eddy-current losses and circulating-current losses occur in any generator,[5] with a knowledge of the resistivity or conductivity of a material, the designer will be able to determine the magnitude of these losses and be able to predict their impact on the final design.

2.2.4 Magnetic Properties

2.2.4.1 Magnetic Permeability[21,22]

This property is an index of the degree to which a material increases or decreases the magnetic flux density created by a given current. The permeability of a vacuum is generally used as a base value, hence, magnetic permeability is often given as a relative permeability which is the ratio of the permeability of the material to that of a vacuum. Magnetic permeability is usually written as μ, the permeability of a vacuum is usually written as μ_0 and the relative permeability is usually written as μ_r.

2.2.4.2 Magnetic Hysteresis Curves

This curve demonstrates the hysteresis effects in a given

material for different magnetic field intensities. It is presented on a magnetic flux density, B, versus a magnetic field intensity, H, graph. See Figure 2.3. The area of a specific hysteresis loop is the energy loss per magnetic cycle. Two of the most important values which come off the hysteresis curves are residual flux density and coercive force. The residual flux density is that flux density remaining in a material after the magnetic field intensity is returned to zero and is the magnitude of the distance A in Figure 2.3. The coercive force is defined as the magnetic field intensity required to reduce the residual flux density to zero after the material has been steady state cycled in magnetic field intensity. The coercive force is the magnitude of distance B in Figure 2.3.

2.2.4.3 Normal Magnetization Curves

This curve is derived from a family of hysteresis curves for a given material and is the locus of the tips of the hysteresis curves. Within the literature, the normal magnetization curves may be found by themselves without the hysteresis curves from which they were derived.

2.2.4.4 Saturation Magnetic Field Intensity

Saturation magnetic field intensity is defined as that field intensity at which the material reaches the state of saturation. Magnetic saturation is the state at which for further increases in the magnetic field intensity or magnetizing force, there is no further increase in magnetic flux density over that of free space.[21]

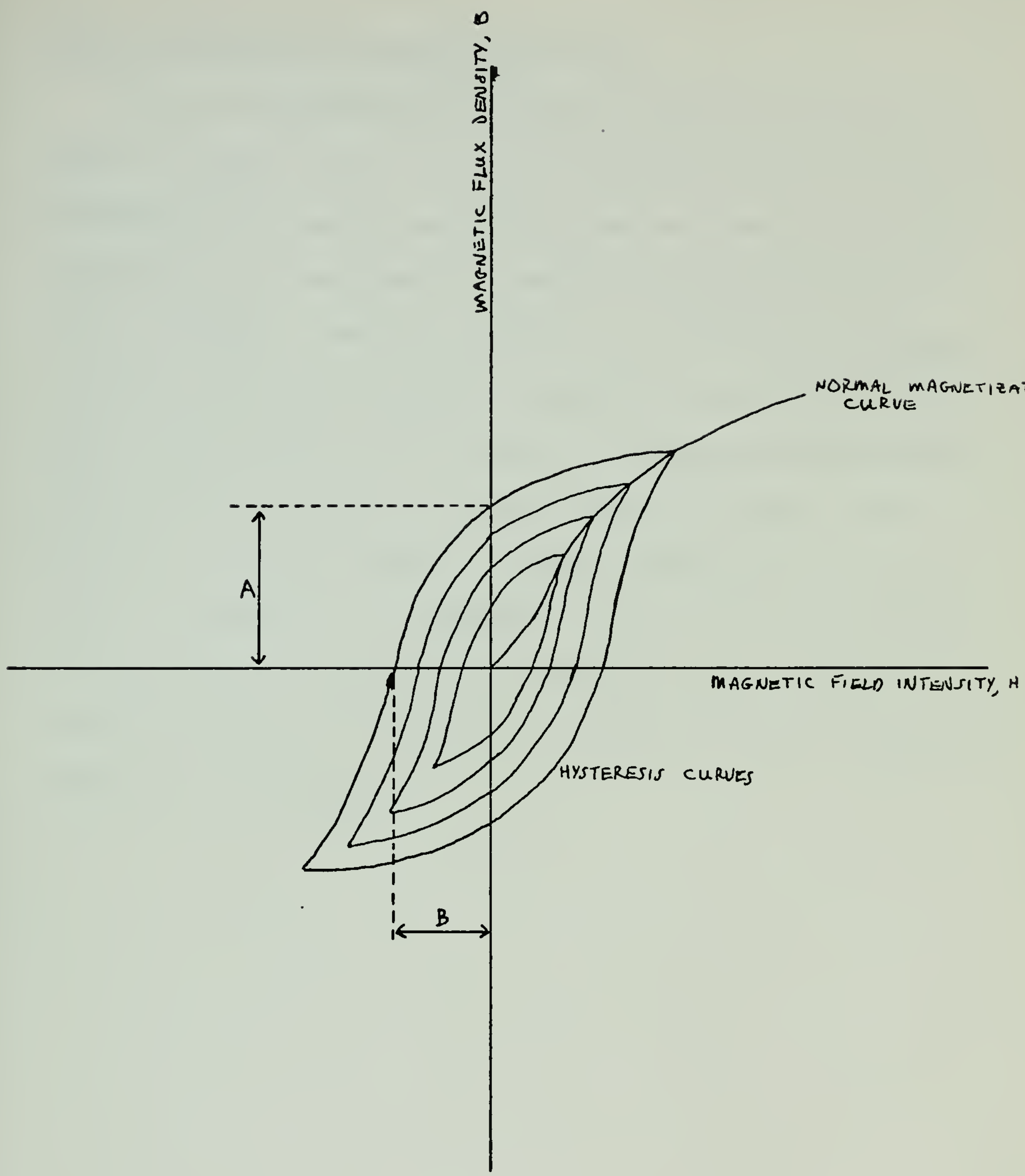


Figure 2.3 Typical Hysteresis Curves and Normal Magnetization Curve

2.2.4.5 Usefulness of Magnetic Properties

In electrical generators and motors where the interaction of magnetic fields are used to create the desired result, the magnetic properties of the machine materials become very important. Magnetic permeability is a good measure of whether the material in question can be considered a magnetic material or not and is used extensively in magnetic circuit calculations. Magnetic hysteresis curves and their areas provide further insight on the dynamic magnetic behavior and losses of a material and since the magnetic history of the material is usually not known, the normal magnetization curves are used as a compromise in calculations. Saturation field intensities are vital in that without a prior knowledge of their values, it would not be possible to ensure proper operation of those applicable components of the machine.

CHAPTER 3

AVAILABILITY OF EXISTING DATA

3.0 Background

During the initial stages of this thesis, a considerable amount of time and energy was devoted to determining where to find data on cryogenic properties of engineering materials beyond just looking through libraries. In an attempt to save time for those who need this kind of data in the future, much of the information on major data collection centers and periodicals is presented in this chapter including addresses, telephone numbers, and the names of those key people to contact.

Unfortunately there is no one data collection center which by itself can provide all current data on all materials. However, by the use of the largest two or three, a relatively complete set of data or references on a specific material may be assembled. The most extensive data and reference holdings are found in the U.S. government sponsored organizations, particularly those organizations which serve the Department of Defence. Since most material property data is unclassified, it is readily available to anyone who wants it for a nominal fee. Generally the prices charged by the government organizations are less than those charged by the private organizations.

3.1 Major Cryogenic Material Property Data Collection and Research Centers

3.1.1 Cryogenic Data Center, National Bureau of Standards

The Cryogenic Data Center is a division of the National Bureau

of Standards Institute for Materials Research located in Boulder, Colorado. Initially this center dealt exclusively with the thermodynamic, transport, and other thermophysical properties of the principal fluids used at low temperatures, but has since expanded to include all properties of structural engineering materials, both metallic and non-metallic.

This data center gathers references from all over the world and enters the bibliographic information and a synopsis of each work into a master computer storage system which permits easy retrieval. In addition they periodically compile the data from those references into books called National Bureau of Standards Monographs which are excellent reference books.

The services offered by the Cryogenic Data Center to the public are literature searches, a current awareness service, a periodic publication on superconducting devices, preliminary data and advice, and periodic announcements of Cryogenic Laboratory publications and reports.

The literature searches which are available are completely flexible in that they are catered exclusively to what the customer needs. Generally the smallest literature search will cost in the vicinity of $25 while extensive searches, such as that from which Appendix A of this thesis was drawn cost approximately $400. The feasibility and estimated cost of a search can be obtained by telephoning Mr. Neil A. Olien the Project Leader for the Documentation Group at 499-1000, extension 3257, area code 303.

The data center generates weekly a pamphlet entitled the Cryogenic Data Center Current Awareness Service. This is a bibliography of new publications and reports in the broad area of cryogenics. This pamphlet provides nothing more than the usual bibliography entry on each item, but does have a subject index for ease of use. Annual subscriptions cost $20 and are available through the National Technical Information Service (NTIS).

Another pamphlet generated by the data center in collaboration with the Office of Naval Research is a quarterly literature survey entitled Superconducting Devices and Materials. As with the current awareness service, this provides bibliographic entries of new references with a subject index and is available for $20 per year from NTIS.

Preliminary data and advice on the thermodynamic and transport properties of cryogenic fluids and selected solids can be obtained for a pre-arranged fee by contacting Mr. Hans Roder, the Project Leader for the Data Compilation Group at 499-1000, extension 3528, area code 303. This particular service is the only one where numerical data can be obtained from the National Bureau of Standards in Boulder.

The only free service offered by the data center is periodic announcements of Cryogenic Laboratory publications and reports. This service can be obtained by writing Mrs. Jo R. Mendenhall, Cryogenic Data Center, National Bureau of Standards, Boulder, Colorado, 80302, and asking to be placed on the mailing list. With each announcement there is ordering information on each

publication and report.

3.1.2 Mechanical Properties Data Center, Traverse City, Michigan

The Mechanical Properties Data Center has been an Air Force Materials Information Center for fourteen years and is also an officially designated DOD Information Analysis Center. The purpose of this organization is acquisition, evaluation, organization and dissemination of mechanical properties of structural metals and metal alloys.

The services provided by the Mechanical Properties Data Center to the public include data searches, literature searches, and the publication of handbooks. The data searches are done in response only to specific questions; i.e., a data search is defined as the data and information available on each alloy/test type combination specified in a request. The current costs of a data search are a basic charge of $25 plus 25¢ per well defined test result up to a maximum of $75 per search.

The literature searches which are available are also in response only to questions on specific materials and specific properties. The current costs of a literature search are between a minimum of $10 and a maximum of $25 depending on the depth of detail desired and the quantity of pertinent titles identified.

There are two handbooks available from the Mechanical Properties Data Center: the Aerospace Structural Metals Handbook and the Structural Alloys Handbook. The Aerospace Structural Metals Handbook contains complete information on all properties and fabrication characteristics of 210 metals and alloys in temperature ranges down

to approximately 30°K. The Structural Alloys Handbook is designed for use by the construction, heavy equipment, machine tools, automotive, and general manufacturing industries and has relatively little cryogenic data. Both handbooks are up-dated semi-annually for an additional charge.

Detailed information on ordering data, literature searches, or the handbooks is available by calling 947-4500, area code 616, or writing:

Mechanical Properties Data Center
13919 West Bay Shore Drive
Traverse City, Michigan 49684

3.1.3 Metals and Ceramics Information Center, Battelle Memorial Institute

The Metals and Ceramics Information Center is another designated DOD Information Analysis Center. It is sponsored by the Department of Defense Office of Research and Engineering. The objectives of this organization are to collect, evaluate, and disseminate information on the characteristics and utilization of advanced metals, ceramics and selected composites.

The services offered by the Metals and Ceramics Information Center are a monthly bulletin on cryogenic properties of metals, a series of state-of-the-art reports, and literature and data searches. The monthly bulletin is the Review of Metals Technology, Low Temperature Properties of Metals which is sponsored jointly by the Metal Properties Council and the Metals and Ceramics Information Center. It provides condensed data on the recent developments in the area and the sources of this data. There is no master index

associated with this publication, so retrieval of information from past issues is tedious. A subscription for this review is available through NTIS.

The state-of-the-art reports are generated at irregular intervals and the only way to find out what is available is to periodically write the Metals and Ceramics Information Center and ask. This information is available free of charge and copies of these reports are available through NTIS.

There is no set policy concerning data or literature searches on specific topics, however, the feasibility and cost of these searches may be discussed by telephoning Mr. James E. Campbell at 299-3151, extension 3471, area code 614.

More detailed information on all services offered by the Metals and Ceramics Information Center is available by calling 299-3151, area code 614, or writing:

Metals and Ceramics Information Center
Battelle
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

3.1.4 Thermophysical and Electronic Properties Information Analysis Center, Purdue University

The Thermophysical and Electronic Properties Information Analysis Center (TEPIAC) is a part of the School of Engineering at Purdue University and is composed of two groups: the Thermophysical Properties Information Analysis Center and the Electronic Properties Information Center. TEPIAC is sponsored by the Defense Supply Agency, Department of Defense. The objectives of TEPIAC are to gather and

analyze data on thermophysical and electronic (including electrical and magnetic) properties of all types of solids and put this data in a form most useful to the engineering community.

The services available to the public by TEPIAC include bibliographic searches and consultive inquiries, a series of major publications, and a bimonthly newsletter. A bibliographic search is defined as the search for a maximum of five different properties of one material for any temperature range and costs $20 regardless of the number of references retrieved. Copies of the references are available at $1 per microfiche reproduction or 25¢ per hard copy page. Consultive inquiries are charged at $16 per hour with a minimum of $32. If laboratory experiments are needed, they are charged at the same rate as consultive inquiries up to a maximum of $1000. Further information on either bibliographic searches or consultive inquiries is available by telephoning or writing:

Mr. Wade H. Shafer, Assistant Director
Thermophysical Properties Research Center
Purdue Industrial Research Park
Purdue University
2595 Yeager Road
West Lafayette, Indiana 47906

Telephone: 463-1581, area code 317

The major publications written by TEPIAC are available from the publisher and are as follows:

(1) Thermophysical Properties of Matter - This is a massive thirteen volume work published by the IFI/Plenum Data Corporation, 227 West 17th Street, New York, N.Y. 10011. The cost of the entire set is approximately $700. This work is considered the most comprehensive document on the subject currently in existence.

(2) Thermophysical Properties Research Literature Retrieval Guide and Supplement I - These two works are also published by the IFI/ Plenum Data Corporation. The current cost of the Guide is $275 and the cost of the Supplement I is also $275. These works together provide all unclassified references on thermophysical properties of matter up through the end of 1970.

The bimonthly newsletter is entitled the Thermophysics Newsletter and is published by the School of Engineering, Purdue University. It is available free to anyone placing their name on the mailing list by writing to Mr. Wade Shafer who was mentioned earlier. The newsletter contains generalized condensed numerical data on thermophysical properties of materials from recent references along with the bibliographic information on these references. At best it serves to keep someone current on recent developments in the field, and is not particularly useful as a reference in itself.

3.1.5 National Technical Information Service

This organization is a division of the U.S. Department of Commerce and serves as the single largest storage and distribution center of technical reference material in the United States. Publication, storage, and distribution are the sole activities of NTIS and, aside from classified documents, all material is available to the public at a reasonable price. Copies of all government agency funded research reports are maintained along with many reports from other sources.

Because there is such a vast amount of material stored by NTIS, to use them as a source of literature searches on specific cryogenic properties of engineering materials, which is a rather

specialized area of knowledge, is not practical and is extremely expensive: $50 for 100 abstracts and 25¢ for each additional abstract. All documents held by NTIS are filed under individual accession numbers and the best way to use the facilities of NTIS is to determine the documents and their accession numbers from the originating agency such as those mentioned earlier in this chapter and then simply order copies of these documents. Verification of accession numbers and current prices are available by calling 321-8521, area code 703. Payment for a document must accompany the order unless the user has access to an organizational account with NTIS. Further information on NTIS may be most easily obtained by calling 451-0560, area code 703, or by writing:

National Technical Information Service
U.S. Department of Commerce
Springfield, Virginia 22151

3.2 Some Major Cryogenic Material Property Reference Works

Since the practical application of engineering materials at very low temperatures is a relatively new field of engineering, there is not an abundance of large reference works on cryogenic properties of materials. Much of this information is scattered throughout technical journals or exists in government sponsored research reports. Of the eight reference works mentioned in this section, only two are what could be considered attempts at producing comprehensive data sources. The remainder are specialized books on a single property or similar groups of properties, or are books on cryogenic engineering in general with articles on material properties.

3.2.1 Cryogenic Materials Data Handbook[23]

This two volume handbook was prepared by the Martin Marietta Corporation under the sponsorship of the Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. Its official title is Technical Documentary Report AFML-TDR-64-280 of July, 1970. Copies are available to the public from NTIS with the following accession numbers and prices:

Volume I - AD 713619 - $9
Volume II - AD 713620 - $6

The work referenced here is the most recent of what has been a series of up-dated versions of the handbook. Presumably this will be up-dated again in the future.

The handbook contains graphical data on various cryogenic properties of 88 of the most promising non-metallic and metallic engineering materials in the temperature range of 100°F to -460°F. It also contains information on the testing procedures used in generating the data as well as a bibliography. The properties covered by this handbook are:

yield strength (0.2% offset)
tensile strength
elongation
reduction in area
notch tensile strength
fracture toughness
weld tensile strength
stress-strain diagram
modulus of elasticity
impact strength
hardness
modulus of rigidity
compressive strength
compressive modulus
fatigue strength
shear strength

shear modulus
flexural strength
flexural modulus
thermal expansion
Poisson's ratio
thermal conductivity
resistivity
specific heat

This handbook probably represents the single most thorough and current source of data on cryogenic properties of engineering materials. Its major shortcoming is the limited number of materials covered.

3.2.2 A Compendium of the Properties of Materials at Low Temperatures[24]

This is a five volume handbook which was compiled by the Cryogenic Engineering Laboratory, National Bureau of Standards, under the sponsorship of the Air Research and Development Command, United States Air Force, Wright-Patterson Air Force Base, Ohio. Its official title is WADD Technical Report 60-56. Copies of the handbook are available from NTIS with the following accession numbers and prices:

Phase I, Part I - AD 249644 - $9
Phase I, Part II - AD 249786 - $9
Phase I, Part III - PB 171620 - $9
Phase II - AD 272769 - $9
Phase III - (classfied and not available to the public)

Each individual volume, with the exception of the classified volume, will be described separately. The major shortcoming of this handbook is its somewhat dated material, however, some of the data is the only data available.

3.2.2.1 Compendium, Phase I, Part I, Properties of Fluids

This volume of the handbook, while not directly useful to the hardware design of superconducting generators and motors, is

described to provide a complete picture of the document. The data is provided in both graphical and tabular form and covers the temperature range from room temperature to near absolute zero. The properties and fluids covered are:

density	helium
expansivity	hydrogen
thermal conductivity	neon
specific heat	nitrogen
transition heats	oxygen
phase equilibria	air
dielectric constants	carbon monoxide
adsorption	fluorine
surface tension	argon
viscosity	methane

3.2.2.2 Compendium, Phase I, Part II, Properties of Solids

This volume of the handbook provides graphical data on thermal expansion, thermal conductivity, and specific heat of a multitude of engineering materials too numerous to list individually. The properties are covered in the temperature range of 300°K to approximately 4°K.

3.2.2.3 Compendium, Phase I, Part III, Bibliography of References

This volume of the handbook provides all the references used for the data in Parts I and II. It is cross indexed by both material and property for both solids and fluids. Since the entire handbook was published in 1961, many of the references are dated, but as was mentioned earlier may still be the only data available.

3.2.2.4 Compendium, Phase II

This volume of the handbook contains graphical data over a variety of temperature ranges, dependent on the source, for the following properties:

(1) Compressibility factor of gases

(2) Velocity of sound and entropy of fluids
(3) Electrical resistivity of solids (53 pure metallic elements)
(4) Thermal conductivity of solids (44 pure metallic elements, 36 non-ferrous alloys, 9 ferrous alloys and 4 flasses and plastics).

3.2.3 Advances in Cryogenic Engineering(25)

This is a book which has been published annually since 1955. It contains the papers presented at each annual Cryogenic Engineering Conference sponsored by the National Science Foundation. Since the entire spectrum of cryogenic engineering is covered, there are inevitably some papers on properties of engineering materials in each issue. Each volume provides a subject index for ease in use. While the data provided in each volume is limited, a quick search through the subject index of the most recent volumes may provide some useful new property data to the designer.

3.2.4 Proceedings of the Applied Superconductivity Conference(26)

This book, as with Advances in Cryogenic Engineering, contains papers presented at an annual conference, some of which contain data on cryogenic properties of engineering materials. The book contains a subject and author index.

Recently, by mutual agreement, the Applied Superconductivity Conference will be held on even numbered years starting in 1974 while the Cryogenic Engineering Conference will be held on odd numbered years starting in 1975. This will create one volume of papers on cryogenics each year and should provide a small but useful source of new property data.

3.2.5 National Bureau of Standards Monographs

The following subsections will describe three of the NBS monographs devoted to specific areas of cryogenic properties of engineering materials. While these three monographs are not all the monographs dealing with cryogenics, they appear to be the most useful to the superconducting generator and motor designer. It is anticipated that in the future, as more property data is generated, more monographs on the subject will be published.

3.2.5.1 NBS Monograph 13, Mechanical Properties of Structural Materials at Low Temperatures[27]

This book contains graphical data on certain properties of the more commercially available ferrous and non-ferrous alloys in the temperature range of 300°K to 0°K. The properties covered are tensile strength, yield strength at 0.2% offset, elongation and impact energy. Every curve throughout the text is referenced to allow the user to check the original work. While the scope of this monograph is rather narrow, it can provide a starting point for the designer in the selection of structural materials.

3.2.5.2 NBS Monograph 101, Low Temperature Mechanical Properties of Copper and Selected Copper Alloys[28]

This book contains graphical data on certain mechanical properties of copper and some of its alloys in the temperature range of 525°K to 0°K. The mechanical properties are:

- yield strength
- tensile strength
- elongation
- reduction in area
- hardness
- impact energy

creep
fatigue behavior
modulus of elasticity
modulus of rigidity

The book is divided into four sections: the first for quick reference use for those interested in average values, the second with data from most of the investigators who have published results on the mechanical properties of copper and its alloys, the third with tables classifying the investigations not included in section two, and the fourth which lists all references used. This monograph is a very complete reference work and can be extremely useful.

3.2.5.3 NBS Monograph 131, Thermal Conductivity of Solids at Room Temperature and Below[29]

This monograph covers the one property of thermal conductivity for nearly all solid materials from room temperature to approximately 0.2°K. The solid materials include elements, alloys, commercial metals, semiconductors, minerals, polymers, and glasses. The experimental methods used in deriving the data are discussed and a complete bibliography is provided. Despite the limited property scope of this monograph, it is a very complete work on its subject.

3.3 Cryogenic Related Periodicals and Journals

Aside from occasional technical papers on cryogenic properties of engineering materials which occur in several of the engineering journals, there is a handfull of magazines published on a regular basis which deal exclusively with the area of cryogenics. While none of them are devoted entirely to material properties, they do provide insight into the availability of commercial materials and

a feel for the current state-of-the-art in engineering material usage. These periodicals and journals are described briefly in the subsequent sections.

3.3.1 Cryogenics, the International Journal of Low Temperature Engineering and Research

This monthly journal is published by the IPC Science and Technology Press, Ltd., IPC House, 32 High Street, Guilford, Surrey, England. The price per issue is \$6.50 and an annual subscription costs \$65.50. The journal publishes original papers from all over the world on every aspect of cryogenics. It also contains original research and technical notes as well as notes on new equipment, production techniques and forthcoming cryogenic related conferences.

3.3.2 Cryogenic Technology, Official Journal of the Cryogenic Society of America

This journal is published bimonthly by Value Engineering Publications, Inc., 825 South Barrington Avenue, Los Angeles, California, 90049. It is purely an industrial magazine which contains advertisements and a few small technical articles. The current prices are \$3 per issue and \$15 per year.

3.3.3 Cryogenics and Industrial Gases

This journal is published bimonthly by Business Communications, Inc., 2800 Euclid Avenue, Cleveland, Ohio, 44115. It also is a purely industrial magazine but with more emphasis of industrial interest concerning cryogenic gas storage, transportation, and use. The journal is provided free of charge to management and technical personnel who deal in the area of low temperature technology.

3.3.4 LNG/Cryogenics, Journal of Refining, Processing, Transportation and Storage Technology

This journal is published bimonthly by Barrington Publications, Inc., 825 South Barrington Avenue, Los Angeles, California, 90049. It is very much like the previous two journals in that it is an industrial magazine with both advertisements and short articles. It is currently provided free of charge to people who deal in low temperature technology.

3.3.5 Bulletin of the International Institute of Refrigeration

This bulletin is published bimonthly by the Institut International Du Froid, 177, Boulevard Malesherbes, 75017 - Paris, France. Its format is English and French on alternate pages and it contains either articles or short paragraphs on current research, reviews of new books and papers, and announcements and news of interest concerning cryogenics. At the end of each year, an index is published to provide for reference usage of the previous six issues. To receive the bulletin requires becoming a member of the International Institute of Refrigeration which costs the equivalent of 130 francs per year.

3.3.6 Communications from the Kamerlingh Onnes Laboratory of the University of Leiden

This small journal is published bimonthly by the Kamerlingh Onnes Laboratory. Each issue contains three papers by the laboratory staff personnel. The papers tend to be theoretical physics more than anything else, but on occasion a materials property paper will be presented. Every other year a listing of the papers presented during the previous two years is published. The journal is

sent free of charge to those requesting to receive it.

3.3.7 General Engineering Journals

The following is a list of some of the engineering journals carried by most engineering libraries which on occasion have papers on cryogenic properties of engineering materials:

(1) IEEE Transactions on Power Apparatus and Systems

(2) American Society of Heating, Refrigeration, and Air Conditioning Engineers Journal

(3) American Society for Metals, Transactions

(4) Journal of the American Ceramic Society

(5) Transactions of the American Society of Civil Engineers

(6) Transactions of the American Society of Mechanical Engineers

CHAPTER 4

CRYOGENIC PROPERTIES OF MATERIALS

4.0 Background

As was shown in Chapter 3, most data on cryogenic properties of structural materials is scattered throughout numerous books and periodicals making it difficult for the designer to gain an appreciation of the wide range of materials available to him with their equally wide range of property values. This chapter is constructed to provide such an appreciation by consolidating cryogenic property data from many references into a relatively concise package. Through the use of the information provided here, the designer will be able to intelligently eliminate many materials for better reasons than simply saying it has never been used before and at the same time may find that a material he might have never considered otherwise will serve his needs.

The chapter is laid out in the following order. The first part contains a brief but hopefully valuable explanation of the different kinds of materials and for these materials a discussion of methods by which the accepted classification societies have classified the alloys either by major alloying elements or by metallurgical structure. There is also an explanation of the temper designation system used for light-weight alloys. This information is provided only as a background for the designer who is undoubtedly familiar with the different subdivisions of alloys, but may not always have the details at his fingertips as a metallurgist might.

The second portion of this chapter consists of remarks regarding the temperature dependence of the properties of the materials along with remarks on how much data is available in the literature. The last portion of the chapter consists of seventy-six tables consolidating all the property data examined. These data tables provide property data at room temperature and at the lowest temperature listed in the reference. Where there is sufficient data the materials are divided into their different alloy classes, and where there is not much data, the alloy classes are left out. Each entry in the data tables is referenced to its source where further detail may be obtained. In addition, a bibliography of data references is provided following the tables.

4.1 Alloy and Temper Designation Systems

4.1.1 Aluminum and Aluminum Alloys(7,12,30)

On 1 October, 1954, the Aluminum Association adopted a four digit numbering system to identify different aluminum alloys. With the exception of the few aluminum alloys which also have tradenames, this system is almost universally used. The four digit system is as follows:

$$X_1X_2X_3X_4$$

where X_1 indicates the alloy series and, hence, the major constituents, X_2 indicates a variation in the basic alloy composition and X_3 and X_4 indicate either the alloy number within its series or the purity level.

The first digit, X_1, can be from 1 to 8 and designates the 1000-series through the 8000-series aluminums. These different series are:

1xxx series - In this series all compositions are at least 99% pure aluminum. The second digit indicates the control exercised over impurities. If this number is zero, there was no control, and if this number is from one through nine some special control was used. The last two digits indicate the minimum aluminum percentage in excess of 99% to the nearest 0.01%.

2xxx series - In this series the predominant alloying element is copper. The last two digits in this and all subsequent series indicate merely a specific alloy number within its series.

3xxx series - In this series the predominant alloying element is manganese.

4xxx series - In this series the predominant alloying element is silicon.

5xxx series - In this series the predominant alloying element is magnesium.

6xxx series - In this series the predominant alloying elements are both magnesium and silicon.

7xxx series - In this series the predominant alloying element is zinc.

8xxx series - In this series the predominant alloying elements are any elements not included in the other series.

In addition to the four digits used to identify each aluminum alloy, a temper designation code usually is included with the alloy number. This code system is explained in section 4.1.5.

4.1.2 Steels[7,30,31]

There are four general classes of structural steels: carbon steels, high-strength low-alloy steels, low-alloy steels and stainless steels.[30] For the purposes of this thesis, the first three classes will be grouped together and referred to from now on as construction steels while the stainless steels will be referred to specifically as stainless steels. Steels have been classified by two organizations, the American Iron and Steel Institute (AISI) and the Society of Automotive Engineers (SAE). The number names given to steels by these two organizations are identical for most steels. As a result of this fact and the way the steels were named in the data references, in the body of this chapter and the data tables, construction steel names will be preceded by AISI/SAE where appropriate and stainless steel number names will be preceded by AISI.

4.1.2.1 Construction Steels

A basic numbering system for these steels as established by the American Iron and Steel Institute and the Society of Automotive Engineers is as follows:[7,30]

AISI/SAE Number	Average Alloy Content, %
10xx	Plain carbon steel
11xx	Free cutting carbon steel
13xx	Manganese steel, 1.75 Mn
23xx	Nickel steel, 3.5 Ni
25xx	Nickel steel, 5.0 Ni
31xx	Nickel-Chromium steel, 1.25 Ni, 0.65-0.8 Cr

33xx	Nickel-Chromium steel, 3.5 Ni, 1.55 Cr
40xx	Molybdenum steel, 0.25 Mo
41xx	Chromium-Molybdenum steel, 0.5-0.95 Cr, 0.2 Mo
43xx	Ni-Cr-Mo steel, 1.8 Ni, 0.5-0.8 Cr, 0.25 Mo
46xx	Nickel-Molybdenum steel, 1.8 Ni, 0.25 Mo
47xx	Ni-Cr-Mo steel, 1.05 Ni, 0.45, 0.2 Mo
48xx	Nickel-Molybdenum steel, 3.5 Ni, 0.25 Mo
50xx	Chromium steel, 0.3-0.6 Cr
51xx	Chromium steel, 0.8-1.65 Cr
61xx	Chromium-Vanadium steel, 0.8-0.95 Cr, 0.1-0.15 V
81xx	Ni-Cr-Mo steel, 0.3 Ni, 0.4 Cr, 0.11 Mo
86xx	Ni-Cr-Mo steel, 0.55 Ni, 0.5-0.65 Cr, 0.2 Mo
87xx	Ni-Cr-Mo steel, 0.55 Ni, 0.5 Cr, 0.25 Mo
92xx	Silicon-Manganese steel, 1.4-2.0 Si, 0.65-0.85 Mn
93xx	Ni-Cr-Mo steel, 3.25 Ni, 1.2 Cr, 0.12 Mo
94xx	Ni-Cr-Mo-Mn steel, 0.45 Ni, 0.4 Cr, 0.12 Mo, 1.0 Mn
97xx	Ni-Cr-Mo steel, 0.55 Ni, 0.17 Cr, 0.2 Mo
98xx	Ni-Cr-Mo steel, 1.0 Ni, 0.8 Cr, 0.25 Mo

In each of the above AISI/SAE numbers, the xx gives the carbon weight content of the steel in per cent. In other words xx10 means 0.1% carbon and xx20 means 0.2% carbon. Also, some of the steel numbers may be followed by the letter H meaning that the steel has been hardened to some depth within the material.

4.1.2.2 Stainless Steels[31]

There are three major groups of stainless steels established in accordance with their metallurgical structure. Martensitic stain-

less steels derive their name from the martensite component of the material. They are body-centered cubic in structure and are magnetic alloys. Ferritic stainless steels derive their name from the ferite component of the material. They are also body-centered cubic in structure and are magnetic alloys. Austenitic stainless steels derive their name from the austenite component of the material. Unlike the other two there are face-centered cubic and non-magnetic. Within each of these groups, the American Iron and Steel Institute has a separate number for each alloy.

4.1.3 Titanium and Titanium Alloys[12]

Titanium and its alloys are classified by their metallurgical structure as are the stainless steels. There are three major groups. Alpha titanium alloys are predominantly hexagonal-close packed (α phase) and this includes pure titanium. Alpha-beta titanium alloys are a mixture of hexagonal-close packed (α phase) and body-centered cubic (β phase) structures. Beta titanium alloys are predominantly body-centered cubic (β phase) in structure. Titanium alloys are named by listing the percentage of the major alloying elements and their chemical symbol. In other words Ti-5Al-2.5Sn contains 5% aluminum and 2.5% tin as the major alloying elements.

4.1.4 Other Light Metals and Alloys[7]

The American Society for Testing and Materials (ASTM) has a recommended codification system for light metals and alloys. The only materials found in researching this thesis which used this system were the magnesium alloys. However it is possible that other

alloys also use this system and may be encountered in the future. The following letters are used to represent the various alloying elements:

A - Aluminum	M - Manganese
B - Bismuth	N - Nickel
C - Copper	P - Lead
D - Cadmium	Q - Silver
E - Rare earth	R - Chromium
F - Iron	S - Silicon
G - Magnesium	T - Tin
H - Thorium	Y - Antimony
K - Zirconium	Z - Zinc
L - Lithium	

As an example of this system, take the magnesium alloy ZK51A. The Z represents the alloying element zinc, the K represents the alloying element zirconium, the 5 means the alloy contains 5% zinc and the 1 means the alloy contains 1% zirconium. The A indicates that this is the first of these alloys so there might also exist later modifications of the alloy such as ZK51B and ZK51C.

4.1.5 Temper Designation System for Light Metals and Alloys[7]

As with the codification system for light metals and alloys, ASTM has established a recommended temper designation system. As was mentioned in section 4.1.1, this system is used with aluminum alloys and it was found while searching for data to also be used by the magnesium alloys.

The temper designation follows the alloy designation and is separated from it by a dash. The basic system is as follows:

-F   As-fabricated

-O   Annealed, recrystallized (wrought products only)

-Hxx Strain-hardened only (-12, quarter hard; -14, half hard; -18, full hard; -19, extra hard)

-H2x Strain-hardened to harder temper and then partially annealed to strength indicated (second digits have same significance as in -H1x series)

-H3x Strain-hardened to temper indicated (same as -H1x series) and then stabilized by low temperature heating to increase ductility

-W Solution heat-treat (an unstable temper), used only with those alloys which age spontaneously at room temperature after solution heat-treatment

-T Treated to produce stable tempers, other than -F, -O, or -H, with or without supplementary strain-hardening (followed by one or more digits)

-T2 Annealed (casting products only)

-T3 Solution heat-treated, and then cold worked, then naturally aged

-T4 Solution heat-treated and naturally aged to a substantially stable condition

-T5 Artificially aged only (without prior solution heat-treatment)

-T6 Solution heat-treated and then artificially aged

-T7 Solution heat-treated and then stabilized (aged beyond the point of maximum hardness to control growth or residual stress)

-T8 Solution heat-treated and cold worked, then artificially aged

-T9 Solution heat-treated and artificially aged, then cold worked

-T10 Artificially aged and then cold worked (castings only)

For the various -H and -T tempers, sometimes there are more following digits than mentioned above. These extra digits indicate special sets of properties too numerous to mention here, however, this information may be found by referring to the latest revision of

ASTM Designation B296.

4.2 Discussion of Cryogenic Properties of Materials

4.2.1 Mechanical Properties

4.2.1.1 Tensile Properties

For the purposes of this discussion, the following properties are grouped under the category of tensile properties: yield strength, ultimate tensile strength, modulus of elasticity, proportional limit, Poisson's ratio, percentage elongation and percentage reduction in area.

It is true for most materials that yield strength, tensile strength, modulus of elasticity and proportional limit all increase as the testing temperature decreases. Since the stress that a given machine part will be required to withstand will vary widely depending on the function of the part, the initial criteria of material selection is best based on the ductility of the material at low temperature. Generally, the ductility of most materials decreases as the testing temperature decreases. However even this criteria may be mitigated somewhat if the ductility of the material is not that crucial.

There is another important factor to be considered in the selection of which material to use. The fewer impurities, interstitial elements, amount of inclusions and surface discontinuities in the material, the better the ductility of the material at low temperatures.(32) This statement is true of all materials and must be considered since the property data available seldom specifies the purity of the material.

4.2.1.1.1 Aluminum and Aluminum Alloys

Tables 4.1, 4.2, 4.17 and 4.25 give the tensile properties of several aluminum alloys. The 1000, 2000, and 5000 series alloys have the greatest ductility at low temperatures. The 7000 series alloys are also reasonably ductile at low temperatures except when tested in sheet form where they become brittle.[32]

With regard to strength, the 2000, 5000 and 7000 series alloys have the highest yield and ultimate tensile strengths at low temperatures. The 5000 series have the added advantage of being weldable. Of the alloys within these series, those which are solution treated and/or artificially aged appear to be the strongest. However, as was mentioned earlier, this high strength may not be necessary for all machine parts.

The cast aluminum alloys are considerably poorer than all the other aluminum alloys with regard to both strength and ductility. This is true at room temperature and doubly true at cryogenic temperatures. These materials are so brittle at cryogenic temperatures - on the order of 1% to 5% elongation at 20°K - that for all practical purposes, they may be eliminated from consideration.

4.2.1.1.2 Copper and Copper Alloys

Tables 4.3, 4.4 and 4.18 give the tensile properties of copper and copper alloys. From the data available, it appears that all the copper alloys have excellent ductility at low temperatures. The strongest alloys are the copper-silicon and copper-beryllium alloys. Therefore, depending on the strength required, this entire class of material is excellent for low temperature use in

the area of tensile properties.

4.2.1.1.3 Nickel and Nickel Alloys

Tables 4.5, 4.6, and 4.19 give the tensile properties of nickel and nickel alloys. The least ductile alloys at low temperature are Inconel X, S-Monel, René 41, Waspaloy, AL-718 and L-605, however, they may still have sufficient ductility for certain cryogenic uses. All of these materials with the exception of pure nickel have extremely high strengths at low temperatures. These alloys, often referred to as "superalloys", were originally developed for high temperature use and therefore may best be used for those parts of a machine which will be subjected to both high and low temperatures.[32]

4.2.1.1.4 Ferrous Materials

Tables 4.7, 4.8, 4.20 and 4.25 give the tensile properties of ferrous materials. The only group of ferrous materials which have been used for low temperature structural applications have been the austenitic stainless steels and the data in the tables demonstrates the reason. All the construction steels and martensitic stainless steels are extremely brittle at low temperatures. Even the austenitic stainless steels, AISI 202, AISI 304L, AM-350, AM-355, Tenelon and 17-7PH are probably too brittle for use at low temperatures. However, all the remaining members of this class have good low temperature ductility. With regard to strength, all ferrous materials including those with low temperature brittleness are extremely strong and compare favorably in this area with the nickel alloys.

4.2.1.1.5 Titanium and Titanium Alloys

Tables 4.9, 4.10, 4.21 and 4.25 give the tensile properties of titanium and titanium alloys. Of all the alloys of this type, only three appear to have adequate ductility for low temperature use - pure titanium and Ti-5Al-2.5Sn of the alpha group and Ti-6Al-4V of the alpha-beta group. Ti-6Al-4V, while its percentage elongation is lower than the other two, has been used for helium pressure bottles in aerospace applications.[32] Ti-5Al-2.5Sn on the other hand is weldable making it an even more attractive material. All of the titanium alloys are extremely strong both at room and low temperatures, but possibly the overriding virtue of these alloys is their low weight for their high strengths.

4.2.1.1.6 Miscellaneous Metals

Tables 4.11, 4.12, 4.22 and 4.25 give the tensile properties of other miscellaneous metals found in searching for data. The magnesium alloys have strengths in the same range as many of the copper alloys, but their ductility is considerably less both at room and low temperatures. The cobalt alloys have extremely high strengths, but have poor low temperature ductilities. Tantalum retains high ductility at low temperatures and is moderately strong while columbium is extremely brittle at low temperatures. In general, it is safe to say that these metals offer no mechanical advantage over the more available alloys.

4.2.1.1.7 Composite Materials

Tables 4.13, 4.14 and 4.23 give the tensile properties of composite materials. Given that there are so many composite

materials and so relatively little data available, it is impossible to make any meaningful statements on these materials. From the limited data in the tables it appears that the specific materials which have been tested are brittle at all temperatures even though some of them have surprisingly high strengths at room and low temperatures.

4.2.1.1.8 Polymers

Tables 4.15, 4.16 and 4.25 give the tensile properties of polymers. There is even less data available on polymers than on composite materials. However, of the few polymers covered, some of which are very ductile at room temperature, all are brittle and have low strengths at low temperatures.

4.2.1.2 Torsional Properties

There are three properties grouped under the category of torsional properties: shear yield strength, shear ultimate tensile strength and modulus of rigidity. The little property data that was found is presented in Tables 4.26 and 4.27. There is definitely a need for more data in this area, particularly for use in shaft design. Current industrial practice in shaft design is to modify either the tensile yield strength of ultimate tensile strength of a material by an appropriate numerical factor to yield a safe maximum shear stress which the shaft material must be able to withstand. These numerical factors are based on years of experience, but until such experience is gained in superconducting generator and motor design, the designer will need torsional data which is not available today.

4.2.1.3 Notch Toughness

Tables 4.28 through 4.40 provide data on the notch toughness of many materials. The major difficulty in evaluating the notch toughness of a material, as was mentioned in Chapter 2, is the lack of uniformity in testing methods and lack of agreement between metallurgists as to which test is a true measure of the toughness of a material. All of the data found fell into the two categories of impact energy or notch tensile strength. Even within these two categories there were variations. Impact energy in foot-pounds was provided from the following different tests:

Charpy V-notch test
Charpy K-notch test
Charpy U-notch test
Charpy Key-hole test
Izod test
Unspecified impact test

The notched tensile tests were equally diverse since the notches used are not all the same. Each notch was specified in terms of a stress concentration factor defined in reference 13, but the values range from K_t=3 to K_t=21.

What all of this implies is that it is extraordinarily difficult to be able to generalize on the notch toughness of materials relative to each other even with the large amount of data available in the tables. Several materials such as the austenitic stainless steels, Ti-5Al-2.5Sn, Ti-6Al-4V, and some of the magnesium alloys have been used at cryogenic temperatures(27,32,33,34) and have demonstrated adequate notch toughness for their particular use. However, taking the magnesium alloys as an example, the data in Table 4.38 would seem to imply that

they have very poor toughness at room and low temperatures based on their impact energies. Many of the references examined state that specific materials have good toughness at low temperatures, but do not specify for what use and do not substantiate their claim with data. Therefore for the purposes of the designer, aside from restricting himself to those materials which have already been used, the best alternative may be to examine the data for which materials have the highest impact energies and notch tensile strengths and then attempt to design the part in question to avoid as many stress concentrations as possible.[32]

4.2.1.4 Fatigue Properties

There are four properties grouped under this area: the S-N curve, the endurance limit, fatigue strength and the notch sensitivity index. The data found is presented in Table 4.41 through Table 4.52. Here again as with notch toughness, it is very difficult because of the amount of data and the way the data is given to be able to draw any significant conclusions. All of the data, with the exception of Table 4.52, which gives the endurance limit of a mere four aluminum alloys, was found as fatigue strength or notch fatigue strength versus life cycles. As was explained in Chapter 2, fatigue strength is a property derived from the S-N curve, so it would seem more useful for the data to have been presented as S-N curves. Also, the data found is for tests within a relatively narrow band of stresses with only flexure and axial loads considered. Each group of test data includes the value of the stress ratio, R, which is defined as the minimum stress divided

by the maximum stress.

In any case, this is the data available today and as long as the fatigue loads of the part being designed fall within the constraints of the data, the data will be useful. It is felt that this is an area of material properties where extensive further investigation is needed, particularly as the potential usefulness of superconducting generators and motors grow.

4.2.2 Thermophysical Properties

4.2.2.1 Thermal Conductivity

Tables 4.53 through 4.61 present the large amount of data on thermal conductivity of various materials in BTU/HR-FT-°F. Along with the tensile properties of materials, this property seems to be one of the most heavily researched. In general the thermal conductivity of a material drops dramatically with temperature with the four exceptions of OFHC Copper, pure nickel, pure silver and pure gold which have large increases with decreasing temperature. Not surprisingly, the groups of materials with the highest thermal conductivity at room and low temperature are the aluminum and copper alloys. Most of the other materials have low temperature thermal conductivities on the order of 1 BTU/HR-FT-°F or less with the composite materials and polymers having the smallest values.

4.2.2.2 Specific Heat

Table 4.62 gives the almost non-existent experimental data on specific heat of materials at low temperatures. The reason for this lack of hard data most probably lies in the fact that there

are accepted analytical methods such as the Debye equations for approximating the specific heat of solids at all temperatures. At the present time, these methods seem to be the only alternatives for the designer.

4.2.2.3 Linear Thermal Expansion Coefficient

Tables 4.63 through 4.70 give data on the linear thermal expansion coefficient of various materials. This property, as with the tensile properties and thermal conductivity has been heavily researched. Almost all of the data found was derived from the following equation:

$$\alpha = \frac{\text{length at testing temp. - length at room temp.}}{\text{length at room temp.}}$$

The few exceptions to this are the data where the coefficient is normalized to absolute zero. In other words the coefficient is assumed to be zero at 0°K, thus creating a non-zero value at room temperature.

Generally speaking, the alloys with the greatest contraction at low temperatures are the aluminum alloys with coefficient values in the range of -0.004 inches per inch. The materials with the least contraction at low temperatures are the titanium alloys and the polymers with coefficient values in the range of -0.001 inches per inch or less. Of the remaining alloys, copper alloys and ferrous materials have generally greater low temperature contraction than the nickel alloys. The only group of materials which has a wide spread of coefficient values are the composites whose coefficients range from greater than those of the aluminum alloys to less than those of the titanium alloys.

4.2.2.4 Density

Absolutely no data on cryogenic temperature density of materials was found. While this seems surprising, the designer may obtain a good low temperature approximation by using the room temperature density available in any handbook, along with the linear thermal expansion coefficient for a hypothetical bar of unit cross-sectional area and unit length.

4.2.3 Electrical Properties

4.2.3.1 Electrical Resistivity

Tables 4.71 through 4.75 give the limited data available on the electrical resistivity of various structural materials. All of the data, regardless of how presented in its source, has been converted to the units of ohm-meter. From the data available, the best electrical conductors at low temperature are the aluminum and copper alloys just as they are at room temperature. In addition, within these two classes of materials, pure aluminum and pure copper are better conductors than most of their alloys.

4.2.4 Magnetic Properties

The properties which are grouped within this area are: permeability, the hysteresis curves, the normal magnetization curves and the saturation magnetic field intensity. Table 4.76 contains the only data found. This lack of data is most probably a result of the fact that interest in superconducting generators and motors is relatively new combined with the fact that most sturctural materials which have been used or are being considered

for use at cryogenic temperatures are non-magnetic materials with magnetic permeabilities on the order of free space.

DATA TABLES

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
1100-0 (7,8)	5000 (RT)	6250 (75°K)	13000 (RT)	24500 (75°K)
1100-H12 (7,8)	14000 (RT)	16500 (75°K)	16000 (RT)	27000 (75°K)
1100-H14 (7), bar	16000 (RT)	22000 (20°K)	18000 (RT)	48000 (20°K)
1100-H16 (7,8), bar	17750 (RT)	22000 (20°K)	19000 (RT)	31500 (20°K)
1100-H18 (7,8), bar	22500 (RT)	25500 (75°K)	23000 (RT)	33750 (75°K)
2011-T3 (7), bar	46000 (RT)	57000 (75°K)	58000 (RT)	73000 (75°K)
2011-T8 (7), bar	42000 (RT)	52000 (75°K)	58000 (RT)	72000 (75°K)
2014-0 (7), bar, rolled, drawn	10000 (RT)	11000 (75°K)	27000 (RT)	38000 (75°K)
2014-T4 (7), bar, rolled, forged, extruded	43000 (RT)	56000 (75°K)	66000 (RT)	83000 (75°K)
2014-T6 (5,8), sheet longitudinal	66900 (RT)	84750 (20°K)	70200 (RT)	100600 (20°K)
2014-T6 (5,8), sheet transverse	65100 (RT)	83600 (20°K)	72550 (RT)	97500 (20°K)
2014-T6 (5), forged	59800 (RT)	85500 (20°K)	67500 (RT)	104000 (20°K)

Table 4.1 Yield and Ultimate Tensile Strength of Aluminum Alloys in PSI.

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
2014-T6[7], forged, rolled	61000 (RT)	70000 (75°K)	70000 (RT)	82000 (75°K)
2014-T651[8], plate longitudinal	64000 (RT)	82000 (4.2°K)	69000 (RT)	95000 (4.2°K)
2014-T651[8], plate transverse	63000 (RT)	85000 (75°K)	70000 (RT)	97000 (75°K)
2017-T61[7], bar	37000 (RT)	51000 (75°K)	59000 (RT)	78000 (75°K)
2018-T61[7], bar	51000 (RT)	57000 (75°K)	63000 (RT)	75000 (75°K)
2020-T6[8], bar	74000 (RT)	92000 (20°K)	83000 (RT)	110000 (20°K)
2020-T6[8], sheet	78000 (RT)	97000 (20°K)	83000 (RT)	110000 (20°K)
2021-T81[8]	63000 (RT)	85000 (20°K)	73000 (RT)	100000 (20°K)
2024-0[7], bar	11000 (RT)	15000 (75°K)	31000 (RT)	46000 (75°K)
2024-T3[5,17], sheet longitudinal	52350 (RT)	75550 (20°K)	71500 (RT)	111000 (20°K)
2024-T3[5,17], sheet transverse	43900 (RT)	68700 (20°K)	65800 (RT)	106000 (20°K)
2024-T3[7], bar	56000 (RT)	78000 (20°K)	73000 (RT)	111000 (20°K)
2024-T4[5,7,8,18], bar	49475 (RT)	75500 (20°K)	69400 (RT)	103300 (20°K)

Table 4.1 Yield and Ultimate Tensile Strength of Aluminum Alloys in PSI (cont.)

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
2024-T6[8]	63000 (RT)	77000 (20°K)	71000 (RT)	97000 (20°K)
2024-T851[8], plate longitudinal	66000 (RT)	91000 (4.2°K)	73000 (RT)	105000 (4.2°K)
2025-T6[7]	36000 (RT)	NO DATA	30000 (RT)	60000 (20°K)
2218-T61[7], bar	43000 (RT)	53000 (75°K)	59000 (RT)	73000 (75°K)
2219-T6[8]	45000 (RT)	63000 (20°K)	62000 (RT)	93000 (20°K)
2219-T62[5,8], sheet longitudinal	39000 (RT)	54000 (20°K)	58150 (RT)	91100 (20°K)
2219-T62[5,8] transverse	38100 (RT)	52200 (20°K)	57700 (RT)	90300 (20°K)
2219-T81[8], sheet, longitudinal	49500 (RT)	66500 (20°K)	67500 (RT)	98500 (20°K)
2219-T81[8], sheet transverse	52000 (RT)	68000 (20°K)	67000 (RT)	96000 (20°K)
2219-T87[8], sheet longitudinal	57000 (RT)	72600 (20°K)	68600 (RT)	98600 (20°K)
2219-T87[8], sheet transverse	55000 (RT)	71000 (20°K)	68500 (RT)	99500 (20°K)

Table 4.1 Yield and Ultimate Tensile Strength of Aluminum Alloys in PSI (cont.)

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
2618-T6[8], sheet longitudinal	52000 (RT)	67000 (20°K)	58000 (RT)	87000 (20°K)
2618-T6[8], sheet transverse	52000 (RT)	63000 (20°K)	58000 (RT)	87000 (20°K)
2618-T62[8], sheet longitudinal	52000 (RT)	63000 (20°K)	59000 (RT)	87000 (20°K)
2618-T62[8], sheet, transverse	52000 (RT)	63000 (20°K)	58000 (RT)	87000 (20°K)
2618-T651[8], plate, longitudinal	58000 (RT)	72000 (20°K)	63000 (RT)	87000 (4.2°K)
3003-0[7,8], bar	6000 (RT)	8500 (75°K)	17500 (RT)	33000 (75°K)
3003-F[7], plate	8000 (RT)	10500 (75°K)	17000 (RT)	36000 (75°K)
3003-H12[7,8], bar	17500 (RT)	23000 (75°K)	18000 (RT)	34000 (75°K)
3003-H14[8], bar	21500 (RT)	30000 (4.2°K)	23000 (RT)	58000 (4.2°K)
3003-H16[8]	25000 (RT)	30000 (75°K)	26000 (RT)	40000 (75°K)
3003-H18[7,8], bar	26000 (RT)	32250 (75°K)	29000 (RT)	43000 (75°K)
3004-0[7], bar	11000 (RT)	12000 (75°K)	28000 (RT)	47000 (75°K)
3004-F[7], plate	16000 (RT)	20000 (75°K)	30000 (RT)	48000 (75°K)

Table 4.1 Yield and Ultimate Tensile Strength of Aluminum Alloys in PSI (cont.)

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
3004-H38[8], bar	38000 (RT)	47000 (75°K)	43000 (RT)	60000 (75°K)
4032-T6[7], bar	47000 (RT)	49000 (75°K)	55000 (RT)	68000 (75°K)
5050-0[7], bar	7000 (RT)	9000 (75°K)	22000 (RT)	37000 (75°K)
5050-H38[7], bar	32000 (RT)	38000 (75°K)	36000 (RT)	50000 (75°K)
5050-T34[7], bar	26000 (RT)	31000 (75°K)	32000 (RT)	47000 (75°K)
5052-0[7], bar	14000 (RT)	17000 (75°K)	29000 (RT)	70000 (20°K)
5052-F[7], plate	9000 (RT)	12000 (75°K)	26000 (RT)	42500 (75°K)
5052-H32[7], bar	24000 (RT)	28000 (75°K)	32500 (RT)	51000 (75°K)
5052-H34[7,17], bar	26500 (RT)	33000 (20°K)	34500 (RT)	75500 (20°K)
5052-H38[5,8], sheet longitudinal	38500 (RT)	51200 (20°K)	44000 (RT)	85000 (20°K)
5052-H38[5,8], sheet transverse	39500 (RT)	52800 (20°K)	44250 (RT)	83300 (20°K)
5052-H38[7], bar	33000 (RT)	40000 (75°K)	40000 (RT)	58000 (75°K)
5052-H38[5], sheet longitudinal	40200 (RT)	54000 (20°K)	47600 (RT)	93500 (20°K)
5054-H38[5], sheet transverse	41500 (RT)	56500 (20°K)	49200 (RT)	91000 (20°K)

Table 4.1 Yield and Ultimate Tensile Strength of Aluminum Alloys in PSI (cont.)

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
5056-0[7], bar	22000 (RT)	23000 (75°K)	42000 (RT)	58000 (75°K)
5056-H34[7], bar	40000 (RT)	47000 (75°K)	55000 (RT)	73000 (75°K)
5056-H38[7], bar	50000 (RT)	58000 (75°K)	60000 (RT)	80000 (75°K)
5083-0[7,8], bar	22000 (RT)	26000 (4.2°K)	47500 (RT)	82000 (4.2°K)
5083-0[24], plate	20000 (RT)	25000 (20°K)	47 00 (RT)	85000 (4.2°K)
5083-H39[8], sheet longitudinal	64000 (RT)	79000 (20°K)	71000 (RT)	101000 (20°K)
5083-H39[8], sheet transverse	64500 (RT)	83000 (20°K)	73000 (RT)	99000 (20°K)
5083-H113[7,8], bar	38000 (RT)	45000 (4.2°K)	50000 (RT)	85000 (4.2°K)
5083-H113[24], plate	35000 (RT)	41000 (20°K)	49000 (RT)	90000 (20°K)
5083-H321[8], plate longitudinal	34000 (RT)	41000 (4.2°K)	48000 (RT)	86000 (4.2°K)
5086-0[7,8,19], bar	18300 (RT)	24000 (20°K)	38500 (RT)	77000 (20°K)
5086-0[24], plate	17000 (RT)	21000 (20°K)	40000 (RT)	80000 (20°K)
5086-H32[7], bar	32000 (RT)	37000 (75°K)	43000 (RT)	64000 (75°K)
5086-H34[5,8], sheet longitudinal	36500 (RT)	47000 (20°K)	47200 (RT)	90000 (20°K)

Table 4.1 Yield and Ultimate Tensile Strength of Aluminum Alloys in PSI (cont.)

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
5086-H34[5,8], sheet transverse	35000 (RT)	44000 (20°K)	47500 (RT)	85000 (20°K)
5086-H112[7], bar	18000 (RT)	23000 (75°K)	39000 (RT)	58000 (75°K)
5154-0[7], bar	17000 (RT)	19000 (75°K)	36000 (RT)	76000 (20°K)
5154-H32[7], bar	33000 (RT)	44500 (20°K)	44000 (RT)	82000 (20°K)
5154-H34[7], bar	34000 (RT)	39000 (75°K)	44000 (RT)	56000 (75°K)
5154-H38[5,8], sheet longitudinal	40100 (RT)	54000 (20°K)	47300 (RT)	93250 (20°K)
5154-H38[5,8], sheet transverse	40300 (RT)	56500 (20°K)	49100 (RT)	91000 (20°K)
5154-H38[7], bar	42000 (RT)	50000 (75°K)	51000 (RT)	67000 (75°K)
5356-0[7], bar	19000 (RT)	22000 (75°K)	42000 (RT)	62000 (75°K)
5356-H32[7], bar	32000 (RT)	38000 (75°K)	47000 (RT)	62000 (75°K)
5356-H34[7], bar	40000 (RT)	47000 (75°K)	52000 (RT)	73000 (75°K)
5456-0[7], bar	24000 (RT)	28000 (75°K)	51000 (RT)	66000 (75°K)
5456-0[8,24], plate	23000 (RT)	28500 (4.2°K)	49000 (RT)	85000 (4.2°K)
5456-H24[8], sheet longitudinal	42000 (RT)	57000 (20°K)	54000 (RT)	87000 (20°K)

Table 4.1 Yield and Ultimate Tensile Strength of Aluminum Alloys in PSI (cont.)

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
5456-H24 [8], sheet transverse	41000 (RT)	57000 (20°K)	54000 (RT)	83000 (20°K)
5456-H321 [5], sheet longitudinal	39500 (RT)	52600 (20°K)	57400 (RT)	96400 (20°K)
5456-H321 [5], sheet transverse	39600 (RT)	54100 (20°K)	57900 (RT)	88900 (20°K)
5456-H321 [7], bar	38000 (RT)	28000 (75°K)	51000 (RT)	66000 (75°K)
5456-H321 [8,24], plate longitudinal	34500 (RT)	45000 (4.2°K)	55000 (RT)	94500 (4.2°K)
5456-H343 [8], sheet longitudinal	47000 (RT)	58000 (20°K)	57000 (RT)	85000 (20°K)
5456-H343 [8], sheet transverse	44000 (RT)	57000 (20°K)	58000 (RT)	81000 (20°K)
6053-0 [7], bar	7000 (RT)	9000 (75°K)	17000 (RT)	32000 (75°K)
6053-T4 [7], bar	20000 (RT)	27000 (75°K)	34000 (RT)	51000 (75°K)
6053-T6 [7], bar	32000 (RT)	39000 (75°K)	38000 (RT)	55000 (75°K)
6061-0 [7], bar	7500 (RT)	10000 (75°K)	18000 (RT)	56000 (20°K)
6061-T4 [5], sheet longitudinal	30600 (RT)	47200 (20°K)	40500 (RT)	86800 (20°K)

Table 4.1 Yield and Ultimate Tensile Strength of Aluminum Alloys in PSI (cont.)

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
6061-T4 (5), sheet transverse	26300 (RT)	42600 (20°K)	39700 (RT)	92300 (0°K)
6061-T4 (7), bar	22000 (RT)	28000 (75°K)	38000 (RT)	54000 (75°K)
6061-T6 (5,7,8), sheet longitudinal	40600 (RT)	54000 (20°K)	45600 (RT)	75500 (20°K)
6061-T6 (5,7,8), sheet transverse	39800 (RT)	52500 (20°K)	45400 (RT)	72000 (20°K)
6061-T6 (5), bar forged	38500 (RT)	57600 (20°K)	45100 (RT)	84400 (20°K)
6063-0 (7), bar extruded	7000 (RT)	8000 (75°K)	13000 (RT)	26000 (75°K)
6063-T5 (7), bar extruded	23000 (RT)	23000 (75°K)	28000 (RT)	38000 (75°K)
6063-T42 (7), bar extruded	13000 (RT)	16000 (75°K)	23000 (RT)	33000 (75°K)
6151-T6 (7), bar forged	42000 (RT)	48000 (75°K)	47000 (RT)	55000 (75°K)
7002-T6 (8), sheet longitudinal	55000 (RT)	74000 (20°K)	68000 (RT)	100000 (20°K)
7002-T6 (8), sheet transverse	56500 (RT)	72000 (20°K)	66500 (RT)	96000 (20°K)

Table 4.1 Yield and Ultimate Tensile Strength of Aluminum Alloys in PSI (cont.)

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
7039-T6[8]	58000 (RT)	74000 (20°K)	65000 (RT)	96000 (20°K)
7039-T61[8], plate transverse	52000 (RT)	65000 (20°K)	61000 (RT)	98000 (20°K)
7075-0[7], bar	16000 (RT)	19000 (75°K)	33000 (RT)	50000 (75°K)
7075-T6[5,7,8], sheet longitudinal	70900 (RT)	98000 (20°K)	79500 (RT)	112000 (20°K)
7075-T6[5,7,8], sheet transverse	70600 (RT)	98800 (20°K)	80600 (RT)	114000 (20°K)
7075-T6[5], plate longitudinal	84700 (RT)	114000 (20°K)	92900 (RT)	129000 (20°K)
7075-T6[5], plate transverse	42200 (RT)	NO DATA	47000 (RT)	NO DATA
7075-T6[5,7,8], bar	72600 (RT)	97600 (20°K)	82000 (RT)	109300 (20°K)
7079-T6[5,8], sheet longitudinal	70700 (RT)	94400 (20°K)	77500 (RT)	114250 (20°K)
7079-T6[5,8], sheet transverse	72750 (RT)	103200 (20°K)	77600 (RT)	113750 (20°K)
7079-T6[5,8], 5 inch, billet, long	68500 (RT)	85250 (20°K)	74500 (RT)	92700 (20°K)
7079-T6[5,8], 5 inch billet, trans	62000 (RT)	87000 (20°K)	74600 (RT)	89900 (20°K)

Table 4.1 Yield and Ultimate Tensile Strength of Aluminum Alloys in PSI (cont.)

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
7178-T6[5,8], sheet longitudinal	83500 (RT)	110000 (20°K)	90000 (RT)	123500 (20°K)
7178-T6[5,8], sheet transverse	79500 (RT)	111500 (20°K)	91000 (RT)	127000 (20°K)
7275-T6[5,17], sheet longitudinal	77000 (RT)	97000 (20°K)	85000 (RT)	114500 (20°K)
7275-T6[5,17], sheet transverse	72600 (RT)	95200 (20°K)	83600 (RT)	108000 (20°K)
43[7], sand cast	9000 (RT)	10000 (75°K)	22000 (RT)	25000 (75°K)
142-T77[7], sand cast	22000 (RT)	27000 (75°K)	28000 (RT)	37000 (75°K)
354-T62[25], plate permanent mold cast	45500 (RT)	56100 (20°K)	50180 (RT)	60200 (20°K)
355-T6[5,8], bar sand cast	25500 (RT)	57000 (20°K)	34000 (RT)	63800 (20°K)
355-T6[5], bar permanent mold cast	43600 (RT)	60800 (20°K)	49900 (RT)	70800 (20°K)
355-T7[7], sand cast	35000 (RT)	38000 (75°K)	38000 (RT)	44000 (75°K)
355-T51[7], sand cast	25000 (RT)	28000 (75°K)	28000 (RT)	33000 (75°K)
355-T61[5,8], bar permanent mold cast	33500 (RT)	53000 (20°K)	48000 (RT)	70000 (20°K)

Table 4.1 Yield and Ultimate Tensile Strength of Aluminum Alloys in PSI (cont.)

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
356-T6[8] permanent mold cast	25000 (RT)	35000 (20°K)	37500 (RT)	61000 (20°K)
356-T7[7], sand cast	27000 (RT)	32000 (75°K)	33000 (RT)	40000 (75°K)
356-T61[8], cast	30000 (RT)	48000 (4.2°K)	42000 (RT)	66000 (4.2°K)
356-T62[25], plate permanent mold cast	36700 (RT)	45300 (20°K)	40900 (RT)	55000 (20°K)
TENS-50-T6[8] sand cast	33000 (RT)	44000 (20°K)	42000 (RT)	57000 (20°K)
B218-F[25], plate sand cast	21200 (RT)	28100 (20°K)	41200 (RT)	30800 (20°K)

Table 4.1 Yield and Ultimate Tensile Strength of Aluminum Alloys in PSI (cont.)

MATERIAL	Prop. Limit (upper temp)	Prop. Limit (lowest temp)	E (upper temp)	E (lowest temp)
Pure Aluminum[5]	NO DATA	NO DATA	10.2×10^6 (RT)	11.4×10^6 (4.2°K)
1100-0[8]	7500 (RT)	10000 (20°K)	NO DATA	NO DATA
2014-T6[8], sheet longitudinal	61000 (RT)	83800 (20°K)	10.15×10^6 (RT)	11.75×10^6 (20°K)
2014-T6[8], sheet transverse	61000 (RT)	82000 (20°K)	10.1×10^6 (RT)	11.75×10^6 (20°K)
2020-T6[8], bar	70000 (RT)	88000 (20°K)	10.8×10^6 (RT)	12×10^6 (20°K)
2020-T6[8], sheet longitudinal	NO DATA	NO DATA	11.2×10^6 (RT)	13.7×10^6 (20°K)
2024-T3[8], sheet	NO DATA	NO DATA	10.3×10^6 (RT)	11.5×10^6 (20°K)
2024-T4[8], plate	NO DATA	NO DATA	10.5×10^6 (RT)	11.6×10^6 (20°K)
2024-T86[8], bar	70000 (RT)	88000 (20°K)	NO DATA	NO DATA
2219-T62[8], sheet, longitudinal	40000 (RT)	58000 (20°K)	10.5×10^6 (RT)	11.7×10^6 (20°K)
2219-T62[8], sheet, transverse	40000 (RT)	58000 (20°K)	10.5×10^6 (RT)	11.7×10^6 (20°K)
2219-T81[8], sheet, longitudinal	48000 (RT)	70000 (20°K)	10.3×10^6 (RT)	11.9×10^6 (20°K)

Table 4.2 Proportional Limit and Modulus of Elasticity of Aluminum and Aluminum Alloys in PSI

MATERIAL	Prop. Limit (upper temp)	Prop. Limit (lowest temp)	E (upper temp)	E (lowest temp)
2219-T81[8], sheet, transverse	42000 (RT)	63000 (20°K)	10.4×10^6 (RT)	11.8×10^6 (20°K)
2219-T87[8], sheet, longitudinal	50000 (RT)	72000 (20°K)	10.3×10^6 (RT)	11.7×10^6 (20°K)
2219-T87[8], sheet, transverse	49000 (RT)	69000 (20°K)	10.4×10^6 (RT)	11.8×10^6 (20°K)
5052-H38[8], sheet, longitudinal	NO DATA	NO DATA	10.1×10^6 (RT)	12.4×10^6 (20°K)
5052-H38[8], sheet, transverse	NO DATA	NO DATA	10.1×10^6 (RT)	12.3×10^6 (20°K)
5456-H343[8], sheet	41000 (94°K)	60000 (20°K)	NO DATA	NO DATA
6061-T6[8], sheet longitudinal	39000 (RT)	55000 (20°K)	10.1×10^6 (RT)	11.4×10^6 (20°K)
6061-T6[8], sheet transverse	39000 (RT)	55000 (20°K)	10.3×10^6 (RT)	11.5×10^6 (20°K)
7039-T6[8]	56000 (RT)	75000 (20°K)	10×10^6 (RT)	11.5×10^6 (20°K)

Table 4.2 Proportional Limit and Modulus of Elasticity of Aluminum and Aluminum Alloys in PSI (cont.)

MATERIAL	Prop. Limit (upper temp)	Prop. Limit (lowest temp)	E (upper temp)	E (lowest temp)
7075-T6[8], bar	60000 (RT)	95000 (20°K)	10.5×10^6 (RT)	NO DATA
356-T6[8], permanent mold cast	24000 (RT)	24000 (20°K)	NO DATA	NO DATA
TENS-50-T6[8], sand cast	28000 (RT)	33000 (20°K)	10.8×10^6 (255°K)	11.5×10^6 (20°K)

Table 4.2 Proportional Limit and Modulus of Elasticity of Aluminum and Aluminum Alloys in PSI (cont.)

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
PURE COPPER				
Pure Copper[22], annealed	9000 (RT)	15000 (10°K)	33000 (RT)	60000 (4.2°K)
Pure Copper[22], 26% cold drawn	49000 (RT)	62000 (4.2°K)	52000 (RT)	79000 (4.2°K)
Pure Copper[22], aged	NO DATA	NO DATA	51000 (RT)	84000 (4.2°K)
OFHC[7,8], annealed	11000 (RT)	15000 (20°K)	31500 (RT)	65000 (20°K)
OFHC[7], cold drawn, hard	48000 (RT)	63000 (20°K)	52000 (RT)	77000 (20°K)
COPPER-ZINC ALLOYS (BRASSES)				
Commercial Bronze[8,22] 90Cu,10Zn, annealed	8500 (RT)	15000 (4.2°K)	37000 (RT)	69500 (4.2°K)
Red Brass[8], bar, 84.7Cu, 15.3Zn, 14% cold red	13000 (RT)	19000 (4.2°K)	38000 (RT)	68000 (4.2°K)
Admiralty Brass[8], bar, 72.5Cu, 27.5Zn, annealed	10000 (RT)	21000 (4.2°K)	45000 (RT)	79000 (4.2°K)
70/30 Brass[8,22], bar, 3/4 hard	60000 (RT)	72500 (20°K)	95000 (RT)	13300 (20°K)

Table 4.3 Yield and Ultimate Tensile Strength of Copper and Copper Alloys in PSI

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
Yellow Brass[7], 67Cu, 33Zn, 40% cold drawn	85000 (RT)	102000 (90°K)	86000 (RT)	104000 (90°K)
Naval Brass[7], 60Cu,39Zn, 1Sn, rolled	29000 (RT)	37000 (90°K)	57000 (RT)	81000 (90°K)
Naval Brass[8], 61Cu,39Zn, annealed	30000 (RT)	42000 (4.2°K)	63000 (RT)	100000 (4.2°K)
Leaded Brass[12], 58.5Cu, 40Zn, 1.5Pb	35000 (RT)	50000 (90°K)	57000 (RT)	78000 (90°K)
<u>COPPER-TIN ALLOYS (BRONZE)</u>				
Phosphor Bronze A[8,22]	70500 (RT)	100500 (4.2°K)	76000 (RT)	115000 (4.2°K)
<u>COPPER-SILICON ALLOYS</u>				
Fe-Si Bronze[5], bar	NO DATA	45400 (20°K)	NO DATA	100000 (20°K)
Silicon Bronze A[8], bar, annealed	25000 (RT)	37000 (4.2°K)	62000 (RT)	102000 (4.2°K)
Silicon Bronze[22], 97Cu, 3Si, annealed	16000 (RT)	30000 (4.2°K)	67000 (RT)	100000 (4.2°K)

Table 4.3 Yield and Ultimate Tensile Strength of Copper and Copper Alloys in PSI (cont.)

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
Cu-2Ni-1Si[22], aged	105000 (RT)	120000 (4.2°K)	112000 (RT)	136000 (4.2°K)
COPPER-NICKEL ALLOYS				
Copper-Nickel 10[8,22] bar, annealed	21000 (RT)	24500 (4.2°K)	50000 (RT)	80500 (4.2°K)
Copper Nickel 30[8,22] bar, annealed	19500 (RT)	40000 (4.2°K)	62000 (RT)	103500 (4.2°K)
COPPER-BERYLLIUM ALLOYS				
Berylco-10[5], bar	108000 (RT)	144000 (20°K)	122000 (RT)	175000 (20°K)
Berylco-25[5], bar	148000 (RT)	185000 (77.6°K)	180000 (RT)	204000 (77.6°K)
97.7Cu,2Be,0.3Co[7], wrought, soln treated	35000 (RT)	55000 (90°K)	73000 (RT)	95000 (90°K)
97.7Cu,2Be,0.3Co[7], wrought, soln treated, age hardened	157000 (RT)	173000 (90°K)	190000 (RT)	210000 (90°K)
97.7Cu,2Be,0.3Co[7] wrought, soln treated, 1/2H, age hardened	170000 (RT)	195000 (90°K)	195000 (RT)	215000 (90°K)

Table 4.3 Yield and Ultimate Tensile Strength of Copper and Copper Alloys (cont.)

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
Beryllium Copper[8], sheet, 1/2 hard	80000 (RT)	110000 (20°K)	90000 (RT)	138000 (20°K)
97.8Cu,2.6Co.0.6Be[7] wrought, cold drawn, 1/2 hard	51000 (RT)	70000 (20°K)	60000 (RT)	95000 (20°K)
97.4Cu,2Be,0.6Co[7] cast, soln treated, age hardened	157000 (RT)	160000 (90°K)	167000 (RT)	185000 (90°K)
Beryllium Copper A[8] bar	27000 (RT)	58000 (20°K)	70000 (RT)	117000 (20°K)
Beryllium Copper H[8] bar	100000 (RT)	119000 (20°K)	102000 (RT)	154000 (20°K)
97.3Cu,2.3Co,0.4Be[7] cast, soln treated, age hardened	74000 (RT)	83000 (90°K)	89000 (RT)	112000 (90°K)
96.8Cu,2.6Co,0.6Be[7] wrought, cold drawn 1/2 hard, age hardened		112000 (0°K)	123000 (RT)	138000 (90°K)
98Cu,1.1Be,0.9Zn[7] cold drawn, 1/4 hard, age hardened	105000 (RT)	122000 (90°K)	129000 (RT)	145000 (90°K)

Table 4.3 Yield and Ultimate Tensile Strength of Copper and Copper Alloys in PSI (cont.)

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
OTHER COPPER ALLOYS				
Aluminum Bronze[8,22] Cu-7Al-2Fe, annealed	60000 (RT)	85000 (4.2°K)	87000 (RT)	133000 (4.2°K)
Cu-10Al-5Ni-3Fe[8,22] cast	41000 (RT)	60000 (4.2°K)	102000 (RT)	130000 (4.2°K)

Table 4.3 Yield and Ultimate Tensile Strength of Copper and Copper Alloys in PSI (cont.)

MATERIAL	Prop. Limit (upper temp)	Prop. Limit (lowest temp)	E (upper temp)	E (lowest temp)
PURE COPPER				
Pure Copper[22], annealed	NO DATA	NO DATA	16.5×10^6 (RT)	17.2×10^6 (4.2°K)
OFHC[8], annealed	7000 (RT)	7000 (20°K)	17×10^6 (RT)	20×10^6 (4.2°K)
COPPER-ZINC ALLOYS (BRASSES)				
Commercial Bronze[8], bar, 90Cu,10Zn	NO DATA	NO DATA	15×10^6 (RT)	18×10^6 (4.2°K)
Red Brass[8], bar, 84.7Cu, 15.3Zn, 14% cold red	NO DATA	NO DATA	15×10^6 (RT)	18×10^6 (4.2°K)
Admiralty Brass[8], bar, 72.5Cu, 27.5Zn, annealed	NO DATA	NO DATA	15×10^6 (RT)	16.5×10^6 (4.2°K)
70/30 Brass[8,32], bar, 3/4 hard	90000 (RT)	112000 (20°K)	14×10^6 (RT)	17×10^6 (20°K)
Naval Brass[8], bar, 61Cu,39Zn, annealed	NO DATA	NO DATA	13.5×10^6 (RT)	15×10^6 (4.2°K)
COPPER-TIN ALLOYS (BRONZE)				
Phosphor Bronze A[8,22] Cu-5Sn, 85% cold drawn	NO DATA	NO DATA	15.75×10^6 (RT)	17×10^6 (4.2°K)

Table 4.4 Proportional Limit and Modulus of Elasticity of Copper and Copper Alloys in PSI

MATERIAL	Prop. Limit (upper temp)	Prop. Limit (lowest temp)	E (upper temp)	E (lowest temp)
<u>COPPER-SILICON ALLOYS</u>				
Silicon Bronze A[8], bar, annealed	NO DATA	NO DATA	16×10^6 (RT)	17.5×10^6 (4.2°K)
Silicon Bronze[22], 97Cu,3Si, annealed	NO DATA	NO DATA	15×10^6 (RT)	17.4×10^6 (4.2°K)
Cu-2Ni-1Si[22], aged	NO DATA	NO DATA	21.5×10^6 (RT)	23.5×10^6 (4.2°K)
<u>COPPER-NICKEL ALLOYS</u>				
Copper-Nickel 10[8,22] bar, annealed	NO DATA	NO DATA	18×10^6 (RT)	20.5×10^6 (4.2°K)
Copper-Nickel 30[8,22] bar, annealed	NO DATA	NO DATA	22×10^6 (RT)	22.5×10^6 (4.2°K)
<u>COPPER-BERYLLIUM ALLOYS</u>				
Beryllium Copper A[8], bar	26000 (RT)	50000 (20°K)	17×10^3 (RT)	19×10^3 (20°K)
<u>OTHER COPPER ALLOYS</u>				
Aluminum Bronze[8,22] Cu-7Al-2Fe, annealed	NO DATA	NO DATA	16×10^6 (RT)	16.5×10^6 (4.2°K)
Cu-10Al-5Ni-3Fe[8,22] cast	NO DATA	NO DATA	17×10^6 (RT)	18.7×10^6 (4.2°K)

Table 4.4 Proportional Limit and Modulus of Elasticity of Copper and Copper Alloys in PSI (cont.)

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
99.85% Pure Nickel[7,8] annealed	15000 (RT)	21000 (4.2°K)	60000 (RT)	105000 (4.2°K)
Commercially Pure[7] Ni, as forged	90000 (RT)	118000 (75°K)	104000 (RT)	145000 (75°K)
Hastelloy B[8], sheet, 20% cold red, longitudinal	122000 (RT)	162000 (20°K)	144000 (RT)	221000 (20°K)
Hastelloy B[8], sheet 20% cold red, transverse	121000 (RT)	148000 (20°K)	145000 (RT)	220000 (20°K)
Hastelloy B[8], sheet 40% cold red, longitudinal	168000 (RT)	217000 (20°K)	207000 (RT)	282000 (20°K)
Hastelloy B[8], sheet 40% cold red, transverse	193000 (RT)	250000 (20°K)	200000 (RT)	263000 (20°K)
Hastelloy C[8], sheet soln treated, longitudinal	68000 (RT)	120000 (20°K)	125000 (RT)	201000 (20°K)
Hastelloy C[8], sheet soln treated, transverse	60000 (RT)	105000 (20°K)	125000 (RT)	195000 (20°K)
Hastelloy C[8], sheet 20% cold red, longitudinal	145000 (RT)	200000 (20°K)	108000 (RT)	240000 (20°K)

Table 4.5 Yield and Ultimate Tensile Strength of Nickel and Nickel Alloys in PSI

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
Inconel[7], 10% cold drawn	45000 (RT)	65000 (20°K)	106000 (RT)	157000 (20°K)
Inconel[8], 20% reduced, bar	124000 (RT)	160000 (20°K)	131000 (RT)	182000 (20°K)
Inconel X[5], sheet annealed, longitudinal	118000 (RT)	134000 (20°K)	174000 (RT)	233000 (20°K)
Inconel X[5], sheet annealed, transverse	118000 (RT)	139000 (20°K)	174000 (RT)	234000 (20°K)
Inconel X[5], bar	102000 (RT)	130000 (20°K)	174000 (RT)	208000 (20°K)
Inconel X[8], soln treated and aged	122000 (RT)	140000 (20°K)	177000 (RT)	230000 (20°K)
Inconel 718[8], soln treated and aged	170000 (RT)	230000 (20°K)	195000 (RT)	270000 (20°K)
Inconel 718[8], cold reduced and aged	215000 (RT)	265000 (20°K)	230000 (RT)	305000 (20°K)
Monel[7], annealed	28000 (RT)	67000 (20°K)	75000 (RT)	132000 (20°K)
Monel[7], as forged	50000 (RT)	97000 (20°K)	89000 (RT)	142000 (20°K)
K-Monel[5], sheet age hardened	97300 (RT)	136000 (20°K)	154000 (RT)	200000 (20°K)

Table 4.5 Yield and Ultimate Tensile Strength of Nickel and Nickel Alloys in PSI (cont.)

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
K-Monel[7], cold drawn 45%	90000 (RT)	122000 (20°K)	147000 (RT)	217000 (20°K)
K-Monel[8], sheet, soln treated and aged	105000 (RT)	135000 (20°K)	150000 (RT)	195000 (20°K)
S-Monel[8], cast, annealed	77000 (RT)	107000 (20°K)	110000 (RT)	150000 (20°K)
Nickel-Chromium[7] Resistance Alloy	104000 (RT)	139000 (20°K)	133000 (RT)	190000 (20°K)
Nickel Iron Alloy[7]	62600 (RT)	148300 (20°K)	113250 (RT)	212500 (20°K)
René 41[5], sheet age hardened, longitudinal	138000 (RT)	179000 (20°K)	181000 (RT)	212000 (20°K)
René 41[5], sheet, age hardened, transverse	134000 (RT)	174000 (20°K)	174000 (20°K)	206000 (20°K)
René 41[8], soln treated and aged	115000 (RT)	155000 (20°K)	170000 (RT)	230000 (20°K)
Waspaloy[5], bar	122000 (RT)	163000 (20°K)	195000 (RT)	243000 (20°K)
AL-718[6], forging annealed	166000 (RT)	195000 (20°K)	187000 (RT)	237000 (20°K)

Table 4.5 Yield and Ultimate Tensile Strength of Nickel and Nickel Alloys in PSI (cont.)

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
AL-718[6], cold rolled, strip	161000 (RT)22	229000 (20°K)	198000 (RT)	277000 (20°K)
D-979[8], sheet, annealed	76000 (RT)	119000 (20°K)	148000 (RT)	228000 (20°K)
L-605[8], 20% cold red, sheet	120000 (RT)	210000 (20°K)	170000 (RT)	270000 (20°K)
L-605[8], sheet, 40% cold red	220000 (RT)	310000 (20°K)	280000 (RT)	420000 (20°K)
L-605[8], sheet, annealed	65000 (RT)	140000 (20°K)	140000 (RT)	220000 (20°K)
R-235[8], sheet, soln treated	63000 (RT)	90000 (20°K)	114000 (RT)	168000 (20°K)

Table 4.5 Yield and Ultimate Tensile Strength of Nickel and Nickel Alloys in PSI (cont.)

MATERIAL	Prop. Limit (upper temp)	Prop. Limit (lowest temp)	E (upper temp)	E (lowest temp)
99.85% Pure Nickel[7,8] annealed	19000 (RT)	30000 (20°K)	28×10^6 (RT)	31×10^6 (20°K)
Hastelloy B[8], sheet, 20% cold red	NO DATA	NO DATA	31×10^6 (RT)	32.5×10^6 (20°K)
Inconel[8], bar, 20% cold red	120000 (RT)	155000 (20°K)	32×10^6 (RT)	33.5×10^6 (20°K)
Inconel X[8], bar soln treated and aged	135000 (RT)	155000 (20°K)	31×10^6 (RT)	32×10^6 (20°K)
K-Monel[8], sheet, soln treated and aged	120000 (RT)	140000 (20°K)	26×10^6 (RT)	27×10^6 (20°K)
S-Monel[8], cast, annealed	70000 (RT)	115000 (20°K)	24×10^6 (RT)	24.5×10^6 (20°K)
René 41[8], bar annealed	138000 (RT)	160000 (20°K)	NO DATA	NO DATA
D-979[8], sheet, annealed	NO DATA	NO DATA	27×10^6 (RT)	32×10^6 (20°K)
L-605[8], sheet, annealed	NO DATA	NO DATA	32.5×10^6 (RT)	36×10^6 (20°K)

Table 4.6 Proportional Limit and Modulus of Elasticity of Nickel and Nickel Alloys in PSI

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
IRON AND IRON ALLOYS				
Gray Cast Iron(7)	NO DATA	NO DATA	23000 (RT)	26000 (20°K)
Ingot Iron(7), hot rolled	37000 (RT)	117000 (20°K)	48000 (RT)	117000 (20°K)
Invar(8), bar, 12-15% cold red	90000 (RT)	160000 (20°K)	95000 (RT)	170000 (20°K)
Ni-SPAN-C(8), bar soln treated and aged	110000 (RT)	145000 (20°K)	175000 (RT)	245000 (20°K)
CONSTRUCTION STEELS				
AISI/SAE 1043(21), plate, longitudinal	40000 (RT)	135000 (77°K)	85000 (RT)	135000 (77°K)
AISI/SAE 1043(21), plate, transverse	50000 (RT)	140000 (77°K)	75000 (RT)	140000 (77°K)
AISI/SAE 1075(8), bar, quenched and tempered	100000 (RT)	205000 (20°K)	150000 (RT)	270000 (20°K)
AISI/SAE 4340(7), quenched and tempered	NO DATA	NO DATA	270000 (RT)	330000 (20°K)
AISI/SAE 4340(8), bar, hardened and tempered	162000 (20)	260000 (20°K)	175000 (RT)	250000 (20°K)

Table 4.7 Yield and Ultimate Tensile Strength of Ferrous Materials in PSI

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
AISI/SAE 9310[5], bar, quenched and tempered	98500 (RT)	195000 (20°K)	146000 (RT)	249000 (20°K)
Nickel Alloy Steel[7], 2% Ni, 0.14C, annealed	NO DATA	NO DATA	80000 (RT)	120000 (20°K)
2800 (9% Ni) Steel[8], bar, double normalized, stress relieved	118000 (RT)	209000 (20°K)	125000 (RT)	219000 (20°K)
18% Ni Maraging [8] Steel, 250 Grade, soln treated	150000 (RT)	260000 (20°K)	175000 (RT)	285000 (20°K)
18% Ni Maraging [8] Steel, 250 Grade, soln treated, aged	270000 (RT)	380000 (20°K)	285000 (RT)	380000 (20°K)
H-11 (5% Cr) Steel[8] bar	232500 (RT)	350000 (20°K)	300000 (RT)	352000 (20°K)
STAINLESS STEEL-MARTENSITIC				
AISI 410[8], bar, hardened and tempered	200000 (RT)	265000 (77.6°K)	200000 (RT)	325000 (77.6°K)
AISI 416[8], bar quenched and tempered	172000 (RT)	290000 (20°K)	225000 (RT)	290000 (20°K)

Table 4.7 Yield and Ultimate Tensile Strength of Ferrous Materials in PSI (cont.)

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
17-4PH-H1100[8], bar	180000 (RT)	290000 (20°K)	180000 (RT)	290000 (20°K)
STAINLESS STEEL-AUSTENITIC				
AISI 202[5], bar annealed	20000 (RT)	120000 (20°K)	120000 (RT)	170000 (20°K)
AISI 301[5,8], 3/4 hard	165000 (RT)	222000 (20°K)	190000 (RT)	305000 (20°K)
AISI 301[5,], sheet, full hard	183000 (RT)	250000 (20°K)	205000 (RT)	340000 (20°K)
AISI 301[5,8], sheet, extra hard, cold rolled	169500 (RT)	241500 (20°K)	198000 (RT)	326000 (20°K)
AISI 301[8], extra full hard	195000 (RT)	285000 (20°K)	227000 (RT)	330000 (20°K)
AISI 301N[11], 10% cold rolled	200000 (RT)	297000 (20°K)	223000 (RT)	334000 (20°K)
AISI 301N[5], sheet, extra full hard, longitudinal	191000 (RT)	287000 (20°K)	214000 (RT)	318000 (20°K)
AISI 301N[5], sheet, extra full hard, transverse	171000 (RT)	280000 (20°K)	224000 (RT)	303000 (20°K)

Table 4.7 Yield and Ultimate Tensile Strength of Ferrous Materials in PSI (cont.)

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
AISI 302[5,7,11] annealed	35000 (RT)	125000 (20°K)	98000 (RT)	260000 (20°K)
AISI 302[5,8], sheet, 40% cold rolled, longitudinal	159000 (RT)	221000 (20°K)	176000 (RT)	352000 (20°K)
AISI 302[5,8], sheet, 40% cold rolled, transverse	NO DATA	217000 (20°K)	NO DATA	300000 (20°K)
AISI 302[5,8], sheet, 60% cold rolled, longitudinal	178000 (RT)	250000 (20°K)	207000 (RT)	305000 (20°K)
AISI 302[5,8], sheet, 60% cold rolled, transverse	NO DATA	259000 (20°K)	NO DATA	315000 (20°K)
AISI 303[5,8,11], bar, annealed	55000 (RT)	81000 (20°K)	110000 (RT)	270000 (20°K)
AISI 303[7], 10% cold drawn	40000 (RT)	82000 (20°K)	95000 (RT)	240000 (20°K)
AISI 304[5,7], bar, annealed	34500 (RT)	65000 (20°K)	92000 (RT)	260000 (20°K)
AISI 304[6], plate	33000 (RT)	64000 (20°K)	85000 (RT)	245000 (20°K)
AISI 304[8]	62000 (RT)	85000 (20°K)	100000 (RT)	250000 (20°K)

Table 4.7 Yield and Ultimate Tensile Strength of Ferrous Materials in PSI (cont.)

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
AISI 304L[5], bar annealed	28000 (RT)	33900 (20°K)	85000 (RT)	220000 (20°K)
AISI 304L[11], 50% cold rolled,	158000 (RT)	231000 (20°K)	176000 (RT)	279000 (20°K)
AISI 304L[6], cold rolled, full hard	158000 (RT)	231000 (20°K)	176000 (RT)	279000 (20°K)
AISI 308[7,17], 15% cold drawn	55000 (RT)	88000 (20°K)	95000 (RT)	249000 (20°K)
AISI 310[5,11], bar, annealed	38000 (RT)	107000 (20°K)	92500 (RT)	178000 (20°K)
AISI 310[5,8], sheet, 40% cold rolled, longitudinal	132500 (RT)	200000 (20°K)	156000 (RT)	278000 (20°K)
AISI 310[5,8], sheet, 40% cold rolled, transverse	NO DATA	218000 (20°K)	NO DATA	263000 (20°K)
AISI 310[5,8], sheet, 60% cold rolled, longitudinal	154000 (RT)	231000 (20°K)	174000 (RT)	279000 (20°K)
AISI 310[5,8], sheet, 60% cold rolled, transverse	NO DATA	226000 (20°K)	NO DATA	285000 (20°K)

Table 4.7 Yield and Ultimate Tensile Strength of Ferrous Materials in PSI (cont.)

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
AISI 310 [5,8], sheet 75% cold rolled, longitudinal	157000 (RT)	252000 (20°K)	185000 (RT)	290000 (20°K)
AISI 310 [5,8], sheet 75% cold rolled, transverse	155000 (RT)	248000 (20°K)	NO DATA	298000 (20°K)
AISI 310 [6], cold rolled, extra hard	160000 (RT)	254000 (20°K)	179000 (RT)	281000 (20°K)
AISI 310 [6,7], plate	35000 (RT)	95000 (20°K)	80000 (RT)	180000 (20°K)
AISI 316 [5,6,7,8], annealed	35000 (RT)	84000 (20°K)	87000 (RT)	212000 (20°K)
AISI 316 [7], 25% cold drawn	75000 (RT)	115000 (20°K)	100000 (RT)	195000 (20°K)
AISI 321 [7,8], bar, annealed	45000 (RT)	75000 (20°K)	92500 (RT)	252000 (20°K)
AISI 347 [5,8], annealed	65000 (RT)	75000 (20°K)	95000 (RT)	237000 (20°K)
AISI 347 [5,7], bar, annealed	35000 (RT)	55000 (20°K)	100000 (RT)	220000 (20°K)
AISI 347 [7], 10% cold drawn	70000 (RT)	100000 (20°K)	110000 (RT)	250000 (20°K)

Table 4.7 Yield and Ultimate Tensile Strength of Ferrous Materials in PSI (cont.)

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
AISI 347[17], 25% cold drawn	70000 (RT)	101000 (20°K)	105000 (RT)	250000 (20°K)
A-286[6,8], cold rolled, strip, aged	97000 (RT)	140000 (20°K)	147000 (RT)	231000 (20°K)
A-286[8], soln treated, longitudinal	100000 (RT)	140000 (20°K)	170000 (RT)	240000 (20°K)
A-286[8], soln treated, transverse	110000 (RT)	140000 (20°K)	150000 (RT)	220000 (20°K)
AM-350[5], bar, annealed	50000 (RT)	120000 (20°K)	190000 (RT)	220000 (20°K)
Am-350[7], sheet, tempered	NO DATA	NO DATA	195000 (RT)	265000 (20°K)
AM-350-H[8], bar, annealed	50000 (RT)	110000 (20°K)	170000 (RT)	220000 (20°K)
AM-355[8], sheet, cold rolled, longitudinal	275000 (RT)	330000 (20°K)	290000 (RT)	350000 (20°K)
AM-355[8], sheet, cold rolled, transverse	250000 (RT)	320000 (20°K)	290000 (RT)	340000 (20°K)

Table 4.7 Yield and Ultimate Tensile Strength of Ferrous Materials in PSI (cont.)

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
Tenelon[8], bar, annealed	80000 (RT)	180000 (20°K)	160000 (RT)	180000 (20°K)
17-7PH-TH1050[8], sheet	184000 (RT)	260000 (20°K)	190000 (RT)	262000 (20°K)

Table 4.7 Yield and Ultimate Tensile Strength of Ferrous Materials in PSI (cont.)

MATERIAL	Prop. Limit (upper temp)	Prop. Limit (lowest temp)	E (upper temp)	E (lowest temp)
<u>IRON AND IRON ALLOYS</u>				
Invar[8], bar 12-15% cold red	80000 (RT)	130000 (20°K)	21×10^6 (RT)	19×10^6 (20°K)
Ni-SPAN-C[8], bar, soln treated and aged	100000 (RT)	130000 (20°K)	25.5×10^6 (RT)	24×10^6 (20°K)
<u>CONSTRUCTION STEELS</u>				
AISI/SAE 1075 [8], bar, quenched and tempered	105000 (RT)	255000 (20°K)	30×10^6 (RT)	32×10^6 (20°K)
AISI/SAE 5450[5], annealed	NO DATA	NO DATA	29.8×10^6 (RT)	31.8×10^6 (4.2°K)
AISI/SAE 4340[8], bar, hardened and tempered	NO DATA	NO DATA	29×10^6 (RT)	31×10^6 (20°K)
2800 (20% Ni) Steel[8] bar, double normalized, stress relieved	120000 (RT)	200000 (20°K)	NO DATA	NO DATA
18% Ni Maraging Steel[8] sheet, 250 grade, soln treated	NO DATA	NO DATA	26×10^6 (RT)	27.5×10^6 (20°K)

Table 4.8 Proportional Limit and Modulus of Elasticity of Ferrous Materials in PSI

MATERIAL	Prop. Limit (upper temp)	Prop. Limit (lowest temp)	E (upper temp)	E (lowest temp)
18% Maraging Steel(8) sheet, 250 grade, soln treat and aged	NO DATA	NO DATA	26×10^6 (RT)	28×10^6 (20°K)
H-11 (5% Cr)(8), bar	200000 (RT)	300000 (20°K)	NO DATA	NO DATA
<u>STAINLESS STEELS-MARTENSITIC</u>				
AISI 410(8), bar, hardened and tempered	190000 (RT)	280000 (20°K)	31×10^6 (RT)	32×10^6 (20°K)
AISI 416(8), bar, quenched and tempered	160000 (RT)	265000 (20°K)	NO DATA	NO DATA
17-4Ph-H1100(8), bar	160000 (RT)	260000 (20°K)	28×10^6 (RT)	30×10^6 (20°K)
<u>STAINLESS STEEL-AUSTENITIC</u>				
AISI 301(5)	NO DATA	NO DATA	29.7×10^6 (RT)	32.3×10^6 (4.2°K)
AISI 301(8), sheet, extra full hard	175000 (RT)	320000 (20°K)	33×10^6 (RT)	33×10^6 (20°K)
AISI 301(8), sheet, 60% cold red, longitudinal	200000 (RT)	315000 (20°K)	25×10^6 (RT)	30×10^6 (20°K)
AISI 301(8), sheet, 60% cold red, transverse	175000 (RT)	290000 (20°K)	27×10^6 (RT)	31×10^6 (20°K)

Table 4.8 Proportional Limit and Modulus of Elasticity of Ferrous Materials in PSI (cont.)

MATERIAL	Prop. Limit (upper temp)	Prop. Limit (lowest temp)	E (upper temp)	E (lowest temp)
AISI 302[8], bar, cold reduced	100000 (RT)	125000 (20°K)	NO DATA	NO DATA
AISI 303[8], bar, annealed	55000 (RT)	100000 (20°K)	28×10^6 (RT)	29×10^6 (20°K)
AISI 304[8], bar, annealed	60000 (RT)	110000 (20°K)	28×10^6 (RT)	29×10^6 (20°K)
AISI 304[8], sheet, 60% cold red, longitudinal	170000 (RT)	280000 (20°K)	26×10^6 (RT)	27×10^6 (20°K)
AISI 304[8], sheet, 60% cold red, transverse	180000 (RT)	280000 (20°K)	30×10^6 (RT)	29.5×10^6 (20°K)
AISI 310[8], bar, annealed	35000 (RT)	110000 (4.2°K)	30×10^6 (RT)	32×10^6 (20°K)
AISI 310[8], sheet, 75% cold red	160000 (RT)	275000 (20°K)	27×10^6 (RT)	28×10^6 (20°K)
AISI 321[8], bar, annealed	55000 (RT)	55000 (20°K)	27×10^6 (RT)	29×10^6 (20°K)
AISI 321[8], sheet, annealed	35000 (RT)	65000 (20°K)	NO DATA	NO DATA
AISI 347[8], bar, annealed	60000 (RT)	70000 (20°K)	26×10^6 (RT)	28×10^6 (20°K)

Table 4.8 Proportional Limit and Modulus of Elasticity of Ferrous Materials in PSI (cont.)

MATERIAL	Prop. Limit (upper temp)	Prop. Limit (lowest temp)	E (upper temp)	E (lowest temp)
A-286[8], soln treated	110000 (RT)	110000 (20°K)	28×10^6 (RT)	30×10^6 (20°K)
AM-355[8], sheet, cold rolled	NO DATA	NO DATA	28.5×10^6 (RT)	28.5×10^6 (20°K)
17-7-PH-TH1050[8] sheet	190000 (RT)	240000 (20°K)	27.5×10^6 (RT)	31×10^6 (20°K)

Table 4.8 Proportional Limit and Modulus of Elasticity of Ferrous Materials in PSI (cont.)

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
TITANIUM-ALPHA				
Commercially Pure Ti [8]	80000 (RT)	160000 (20°K)	80000 (RT)	190000 (20°K)
Commercial Grade [7] Ti, RS-70, sheet, annealed	68000 (RT)	172000 (20°K)	86000 (RT)	187000 (20°K)
Ti-Al-2.5Sn [5,8], sheet, annealed	120000 (RT)	240000 (20°K)	125000 (RT)	250000 (20°K)
Ti-5Al-2.5Sn [5], bar	128000 (RT)	264000 (20°K)	135000 (RT)	270000 (20°K)
Ti-5Al-2.5Sn [8] normal interstitial	115000 (RT)	255000 (20°K)	130000 (RT)	250000 (20°K)
Ti-5Al-2.5Sn [8], extra low interstitial	105000 (RT)	215000 (20°K)	110000 (RT)	225000 (20°K)
Ti-5Al-4Zr-1V [5] sheet, annealed	137000 (RT)	264000 (20°K)	140000 (RT)	278000 (20°K)
Ti-5Al-5Zr-5Sn [5], sheet, annealed	120500 (RT)	240000 (20°K)	124000 (RT)	258000 (20°K)
Ti-7Al-12Zr [6], sheet, annealed	133000 (RT)	240000 (20°K)	141000 (RT)	250000 (20°K)

Table 4.9 Yield and Ultimate Tensile Strength of Titanium and Titanium Alloys in PSI

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
Ti-8Al-2Cb-1Ta(5,8), sheet	130500 (RT)	248000 (20°K)	142000 (RT)	264000 (20°K)
Ti-8Al-2Cb-1Ta(8), sheet, annealed	102000 (RT)	172000 (20°K)	112000 (RT)	205000 (20°K)
Ti-8Al-1Mo-1V(8), sheet, annealed	145000 (RT)	230000 (20°K)	150000 (RT)	260000 (20°K)
Ti-8Al-1Mo-1V(8), sheet, duplex annealed	130000 (RT)	210000 (20°K)	145000 (RT)	245000 (20°K)
TITANIUM-ALPHA BETA				
Ti-4Al-3Mo-1V(5), sheet, annealed	NO DATA	NO DATA	NO DATA	272000 (20°K)
Ti-4Al-3Mo-1V(5), sheet, soln treated, aged	148000 (RT)	304000 (20°K)	177000 (RT)	325000 (20°K)
Ti-6Al-4V(8,5,7,25), sheet, annealed	140000 (RT)	265000 (20°K)	150000 (RT)	270000 (20°K)
Ti-6Al-4V(5), bar	129000 (RT)	260000 (20°K)	135000 (RT)	267000 (20°K)
Ti-6Al-4V(8), annealed normal interstitial	127000 (RT)	250000 (20°K)	140000 (RT)	262000 (20°K)

Table 4.9 Yield and Ultimate Tensile Strength of Titanium and Titanium Alloys in PSI (cont.)

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
Ti-6Al-4V[8], extra low interstitial	130000 (RT)	250000 (20°K)	142000 (RT)	255000 (20°K)
Ti-8Mn[5,7], sheet annealed	NO DATA	NO DATA	140000 (RT)	202000 (20°K)
Ti-6Al-6V-2Sn[8], annealed	140000 (RT)	250000 (4.2°K)	150000 (RT)	255000 (4.2°K)
Ti-6Al-6V-2Sn[8], soln treated, aged	180000 (RT)	285000 (4.2°K)	190000 (RT)	320000 (4.2°K)
<u>TITANIUM-BETA</u>				
Ti-13V-11Cr-3Al[5], sheet, soln treated	NO DATA	NO DATA	NO DATA	335000 (20°K)
Ti-13V-11Cr-3Al[7], sheet, cold rolled, annealed	NO DATA	NO DATA	135000 (RT)	270000 (20°K)
Ti-13V-11Cr-3Al[8], soln treated	NO DATA	NO DATA	140000 (RT)	335000 (20°K)

Table 4.9 Yield and Ultimate Tensile Strength of Titanium and Titanium Alloys in PSI (cont.)

MATERIAL	Prop. Limit (upper temp)	Prop. Limit (lowest temp)	E (upper temp)	E (lowest temp)
<u>TITANIUM-ALPHA</u>				
Pure Ti[5,8]	NO DATA	NO DATA	15.1×10^6 (RT)	17.1×10^6 (4.2°K)
Ti-5Al-2.5Sn[5,8]	NO DATA	NO DATA	15.6×10^6 (RT)	17×10^6 (20°K)
Ti-5Al-2.5Sn[8] normal interstitial, annealed	120000 (RT)	235000 (20°K)	16×10^6 (RT)	18×10^6 (20°K)
Ti-8Al-1Mo-1V[8], sheet, annealed	NO DATA	NO DATA	17.5×10^6 (RT)	20×10^6 (20°K)
<u>TITANIUM-ALPHA BETA</u>				
Ti-4Al-3Mo-1V[5], sheet, soln treated, aged	NO DATA	NO DATA	16.3×10^6 (RT)	19.4×10^6 (20°K)
Ti-6Al-4V[5,8], sheet, annealed	NO DATA	NO DATA	15.5×10^6 (RT)	19×10^6 (20°K)
Ti-6Al-4V[8], annealed, normal interstitial	130000 (RT)	260000 (RT)	16×10^6 (RT)	18×10^6 (20°K)
Ti-6Al-4V[5], extra low interstitial	125000 (RT)	240000 (20°K)	NO DATA	NO DATA
Ti-7Mn[5]	NO DATA	NO DATA	16×10^6 (RT)	17.9×10^6 (4.2°K)

Table 4.10 Proportional Limit and Modulus of Elasticity of Titanium and Titanium Alloys in PSI

MATERIAL	Prop. Limit (upper temp)	Prop. Limit (lowest temp)	E (upper temp)	E (lowest temp)
<u>TITANIUM-BETA</u>				
Ti-13V-11Cr-3Al[8], soln treated	130000 (RT)	300000 (20°K)	16×10^6 (RT)	17×10^6 (20°K)

Table 4.10 Proportional Limit and Modulus of Elasticity of Titanium and Titanium Alloys in PSI (cont.)

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
MAGNESIUM ALLOYS				
AZ31B-O[5,7,20], wrought, sheet	21500 (RT)	30500 (20°K)	36500 (RT)	63000 (20°K)
ZE10A-H11 [5,20], sheet, cold worked	25500 (RT)	33000 (20°K)	34000 (RT)	57000 (20°K)
HM31A-F[5,7,20], extruded	37000 (RT)	49000 (20°K)	40500 (RT)	72500 (20°K)
HM21A-T8[5,7,20], wrought sheet	24500 (RT)	28000 (20°K)	31500 (RT)	56000 (20°K)
HK31A-T6[5,7,20], sand cast	16500 (RT)	20000 (20°K)	33000 (RT)	46000 (20°K)
HK31A-O[5,7,20], wrought sheet	18500 (RT)	26500 (20°K)	28500 (RT)	51500 (20°K)
ZK60A-T5[7], extruded	39000 (RT)	58000 (20°K)	47000 (RT)	69000 (20°K)
COBALT ALLOYS				
Haynes 25[5], sheet, 20% cold rolled	126500 (RT)	209000 (20°K)	164000 (RT)	266500 (20°K)
Haynes 25[5], sheet, 40% cold rolled	215000 (RT)	311000 (20°K)	270000 (RT)	408000 (20°K)

4.11 Yield and Ultimate Tensile Strength of Miscellaneous Metals in PSI

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
Elgiloy[8], bar, 45% cold red.	210000 (RT)	280000 (20°K)	250000 (RT)	365000 (20°K)
<u>OTHERS</u>				
Tantalum[5], bar, wrought, stress relieved	55000 (RT)	208000 (20°K)	61000 (RT)	208000 (20°K)
Tantalum[5], bar, recrystallized	24000 (RT)	112000 (20°K)	35000 (RT)	132000 (20°K)
Columbium[5], bar, wrought, stress relieved	36000 (RT)	179000 (20°K)	45000 (RT)	182000 (20°K)
Columbium[5], bar, recrystallized	18000 (RT)	124000 (20°K)	30000 (RT)	152000 (20°K)
Commercially Pure Lead[7] cast	NO DATA	NO DATA	4000 (RT)	10000 (20°K)

Table 4.11 Yield and Ultimate Tensile Strength of Miscellaneous Metals in PSI (cont.)

MATERIAL	Prop. Limit (upper temp)	Prop. Limit (lowest temp)	E (upper temp)	E (lowest temp)
MAGNESIUM ALLOYS				
Pure Magnesium(5)	NO DATA	NO DATA	6.3×10^6 (RT)	6.9×10^6 (4.2°K)
COBALT ALLOYS				
Elgiloy(8), bar 45% cold red	170000 (RT)	245000 (20°K)	27×10^6 (RT)	30×10^6 (20°K)

Table 4.12 Proportional Limit and Modulus of Elasticity of Miscellaneous Metals in PSI

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
TFE Teflon[8], sheet, 25% asbestos filled	500 (RT)	6500 (20°K)	800 (RT)	6600 (20°K)
FEP Teflon[8], 20% glass filled	2000 (RT)	16500 (20°K)	2000 (RT)	16500 (20°K)
TFE Teflon[8], sheet, 116 glass cloth	30000 (RT)	85000 (20°K)	30000 (RT)	85000 (20°K)
FEP Teflon[8], sheet, 116 glass cloth	25000 (RT)	86000 (20°K)	25000 (RT)	86000 (20°K)
EPOXY-FIBERGLAS LAMINATE-181 GLASS CLOTH REINFORCEMENT-PANELS				
Epon 828 Resin[8], S/HTS reinf.	NO DATA	NO DATA	78000 (RT)	126000 (20°K)
Epon 828 Resin[8], E/HTS reinf.	NO DATA	NO DATA	62000 (RT)	121000 (20°K)
Epon 1001 Resin[8], E-Glass reinf.	NO DATA	NO DATA	49000 (RT)	107000 (20°K)
Epon 828 Resin[8], E-Glass reinf.	NO DATA	NO DATA	40000 (RT)	98000 (20°K)
EPOXY-FIBERGLAS LAMINATE-S/901 ROVING REINFORCEMENT-PANELS				
E-787 Resin[8], unidirectional filament, parallel to reinf.	NO DATA	NO DATA	280000 (RT)	300000 (20°K)

Table 4.13 Yield and Ultimate Tensile Strength of Composite Materials in PSI

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
E-787 Resin[8], 1543 cloth reinf., parallel to reinf.	NO DATA	NO DATA	170000 (RT)	220000 (20°K)
E-787 Resin[8], bidirectional filament, parallel to reinf.	NO DATA	NO DATA	148000 (RT)	170000 (20°K)
DER-332/BF_3 Resin[8], bidirectional filament	NO DATA	NO DATA	160000 (RT)	165000 (20°K)
DER-332/DEH 50 Resin[8] bidirectional filament	NO DATA	NO DATA	140000 (RT)	160000 (20°K)
<u>PHENOLIC-FIBERGLAS LAMINATE-E181 GLASS CLOTH REINFORCEMENT-PANELS</u>				
Narmco 507 Resin[8]	NO DATA	NO DATA	38000 (RT)	72000 (20°K)
CTL91LD Resin[8]	NO DATA	NO DATA	52000 (RT)	66000 (20°K)
CTL91LD Resin[8], E/Volan A reinf.	NO DATA	NO DATA	48000 (RT)	69000 (20°K)
<u>POLYESTER-FIBERGLAS LAMINATE</u>				
Selectron 5158 Resin[8] S/901 roving, bi-directional filament, parallel to reinf.	NO DATA	NO DATA	115000 (RT)	133000 (20°K)

Table 4.13 Yield and Ultimate Tensile Strength of Composite Materials in PSI (cont.)

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
Paraplex P/43 Resin[8] 181 cloth reinf.	NO DATA	NO DATA	48000 (RT)	78000 (20°K)
Hetron 92 Resin[8], 181 cloth reinf.	NO DATA	NO DATA	39000 (RT)	85000 (20°K)
HIGH TEMPERATURE POLYESTER-FIBERGLAS LAMINATE				
Laminac 4232 Resin[8], 181 cloth reinf.	NO DATA	NO DATA	41000 (RT)	56000 (20°K)
Vibrin 135 Resin[8], 181 cloth reinf.	NO DATA	NO DATA	32000 (RT)	54000 (20°K)
SILICON-FIBERGLAS LAMINATE-181 GLASS CLOTH REINFORCEMENT				
Narmco 513 Resin[8]	NO DATA	NO DATA	30000 (RT)	80000 (20°K)
Trevarno F-130 Resin[8]	NO DATA	NO DATA	20000 (RT)	75000 (20°K)
POLYMIDE-FIBERGLAS LAMINATE, E181/A1100 GLASS CLOTH REINFORCEMENT				
Westinghouse 1-8 [8] Resin	NO DATA	NO DATA	37000 (RT)	52000 (20°K)

Table 4.13 Yield and Ultimate Tensile Strength of Composite Materials in PSI (cont.)

MATERIAL	Prop. Limit (upper temp)	Prop. Limit (lowest temp)	E (upper temp)	E (lowest temp)
FEP Teflon[8], 20% glass filled	NO DATA	NO DATA	0.15×10^6 (RT)	1.2×10^6 (20°K)
TFE Teflon[8], sheet, 116 glass cloth	NO DATA	NO DATA	0.9×10^6 (RT)	2.15×10^6 (20°K)
FEP Teflon[8], sheet, 116 glass cloth	NO DATA	NO DATA	1×10^6 (RT)	2.45×10^6 (20°K)
EPOXY-FIBERGLAS LAMINATE-181 GLASS REINFORCEMENT-PANELS				
Epon 828 Resin[8], S/HTS reinf.	NO DATA	NO DATA	3.9×10^6 (RT)	4.2×10^6 (20°K)
Epon 828 Resin[8], E/HTS reinf.	NO DATA	NO DATA	4.1×10^6 (RT)	4.9×10^6 (20°K)
Epon 1001 Resin[8], E-glass reinf.	NO DATA	NO DATA	3.4×10^6 (RT)	4.2×10^6 (20°K)
Epon 828 Resin[8], E-glass reinf.	NO DATA	NO DATA	3.5×10^6 (RT)	4.5×10^6 (20°K)
EPOXY-FIBERGLAS LAMINATE-S/901 ROVING REINFORCEMENT-PANELS				
E-787 Resin[8], unidirectional filament	NO DATA	NO DATA	8.2×10^6 (RT)	9.5×10^6 (20°K)
E-787 Resin[8], 1543 cloth reinf.	NO DATA	NO DATA	5.4×10^6 (RT)	6×10^6 (20°K)

Table 4.14 Proportional Limit and Modulus of Elasticity of Composite Materials in PSI

MATERIAL	Prop. Limit (upper temp)	Prop. Limit (lowest temp)	E (upper temp)	E (lowest temp)
E-787 Resin[8], bidirectional filament	NO DATA	NO DATA	5.8×10^6 (RT)	7×10^6 (20°K)
DER-332/BF_3 Resin[8], bidirectional filament	NO DATA	NO DATA	5×10^6 (RT)	6×10^6 (20°K)
DER-332/DEH50 Resin[8] bidirectional filament	NO DATA	NO DATA	5.2×10^6 (RT)	6.7×10^6 (20°K)
PHENOLIC-FIBERGLAS LAMINATE-181 GLASS CLOTH REINFORCEMENT-PANEL				
Narmco 506 Resin[8]	NO DATA	NO DATA	3.6×10^6 (RT)	3.8×10^6 (20°K)
CTL91LD Resin[8]	NO DATA	NO DATA	3.8×10^6 (RT)	4.5×10^6 (20°K)
CTL91LD Resin[8], E/Volan A reinf.	NO DATA	NO DATA	4.7×10^6 (RT)	4×10^6 (20°K)
POLYESTER-FIBERGLAS LAMINATE				
Selectron 5158 Resin[8] S/901 roving, bi-directional	NO DATA	NO DATA	5.8×10^6 (RT)	5.9×10^6 (20°K)
POLYMIDE-FIBERGLAS LAMINATE, E181/A1100 GLASS CLOTH REINFORCEMENT				
Westinghouse 1-8 Resin[8]	NO DATA	NO DATA	2.9×10^6 (RT)	3.2×10^6 (20°K)

Table 4.14 Proportional Limit and Modulus of Elasticity of Composite Materials in PSI (cont.)

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
Mylar[8], 15% crystallinity	13500 (RT)	43000 (20°K)	21000 (RT)	43000 (20°K)
Mylar[8], 55% crystallinity	13500 (RT)	34000 (20°K)	20000 (RT)	34000 (20°K)
TFE Teflon[8], 49-66% crystallinity	2000 (RT)	19000 (20°K)	5000 (RT)	20000 (20°K)
FEP Teflon[8], 44-49% crystallinity	2000 (RT)	24000 (20°K)	4000 (RT)	24000 (20°K)
KEL-F[8], sheet, 40-70% crystallinity	6000 (RT)	22000 (20°K)	5000 (RT)	23000 (20°K)
KEL-F[8], Type 81, sheet, 40-65% crystallinity	NO DATA	NO DATA	5000 (RT)	22000 (20°K)
DER-332/DEH-50[8] Resin	NO DATA	NO DATA	10000 (RT)	13500 (20°K)
E-787 Resin[8]	NO DATA	NO DATA	9200 (RT)	12000 (20°K)
DER-332/BF_3 Resin[8]	NO DATA	NO DATA	9200 (RT)	12000 (20°K)
Polyethylene[12]	NO DATA	NO DATA	1300 (RT)	NO DATA
Polyvinylchloride[12]	NO DATA	NO DATA	7700 (RT)	19700 (77°K)

Table 4.15 Yield and Ultimate Tensile Strength of Polymers in PSI

MATERIAL	σ_{yield} (upper temp)	σ_{yield} (lowest temp)	σ_{uts} (upper temp)	σ_{uts} (lowest temp)
Borosilicate Glass[12] BSC-2 Corning 8370, abraded	NO DATA	NO DATA	7000 (RT)	10400 (20°K)
Borosilicate Glass[12] BSC-2, Corning 8370, unabraded	NO DATA	NO DATA	10400 (RT)	18000 (76°K)
Epon-828/DSA/Empol[27] 1040/BDMA (100/115.9/20/1)	NO DATA	NO DATA	6000 (RT)	14500 (20°K)
Epon 828/DSA/BOHET/[27] BDMA (100/134/26/1)	NO DATA	NO DATA	7000 (RT)	12300 (20°K)
Epon 826/Epon 871/[27] Adiprene L-100/MDCA (35/15/50/27.6)	NO DATA	NO DATA	2500 (RT)	22500 (20°K)
Epon 826/Empol[27] 1040/Z-6077/DSA/BDMA (80/20/20/115.9/1)	NO DATA	NO DATA	5000 (RT)	13200 (20°K)

Table 4.15 Yield and Ultimate Tensile Strength of Polymers in PSI (cont.)

MATERIAL	Prop. Limit (upper temp)	Prop. Limit (lowest temp)	E (upper temp)	E (lowest temp)
Mylar[8], 15% crystallinity	NO DATA	NO DATA	0.7×10^6 (RT)	1.8×10^6 (20°K)
Mylar[8], 55% crystallinity	NO DATA	NO DATA	0.6×10^6 (RT)	1.45×10^6 (20°K)
TFE Teflon[8], 44-66% crystallinity	NO DATA	NO DATA	0.06×10^6 (RT)	0.6×10^6 (20°K)
FEP Teflon[8], 44-49% crystallinity	NO DATA	NO DATA	0.07×10^6 (RT)	0.75×10^6 (20°K)
FEP Teflon[8], sheet	1000 (RT)	19500 (20°K)	NO DATA	NO DATA
TFE Teflon[8], sheet, 52.4% crystallinity	0 (RT)	10000 (20°K)	NO DATA	NO DATA
TFE Teflon[8], sheet, 72.2% crystallinity	0 (RT)	8000 (20°K)	NO DATA	NO DATA
KEL-F[8], sheet, 40-70% crystallinity	NO DATA	NO DATA	0.23×10^6 (RT)	1.1×10^6 (20°K)
KEL-F[8], Type 81, sheet, 40-65% crystallinity	2000 (RT)	16000 (20°K)	NO DATA	NO DATA
DER-332/DEH 50[8] Resin	NO DATA	NO DATA	0.35×10^6 (RT)	1.2×10^6 (20°K)
E-787 Resin[8]	NO DATA	NO DATA	0.5×10^6 (RT)	1.45×10^6 (20°K)

Table 4.16 Proportional Limit and Modulus of Elasticity of Polymers in PSI

MATERIAL	Prop. Limit (upper temp)	Prop. Limit (lowest temp)	E (upper temp)	E (lowest temp)
DER-332/BF_3 Resin[8]	NO DATA	NO DATA	0.45×10^6 (RT)	1.2×10^6 (20°K)
Polyethylene[12]	NO DATA	NO DATA	0.02×10^6 (RT)	NO DATA
Polyvinylchloride[12]	NO DATA	NO DATA	0.52×10^6 (RT)	1.11×10^6 (20°K)
Epon 828/DSA/Empol 1040/BDMA (100/115.9/20/1) Resin[27]	4000 (RT)	12000 (20°K)	3×10^6 (RT)	9.7×10^6 (20°K)
Epon 828/DSA/BOHET/BDMA (100/134/26/1) Resin (27)	5000 (RT)	11000 (20°K)	3.5×10^6 (RT)	9.6×10^6 (20°K)
Epon 826/Epon 871/Adiprene L-100/MDCA (35/15/50/27.6) (27)	600 (RT)	20000 (20°K)	0.2×10^5 (RT)	13×10^6 (20°K)
Epon 826/Empol 1040/Z-6077/DSA/BDMA (30/20/20/115.9/1)[27]	3500 (RT)	12000 (20°K)	3×10^5	9×10^5

Table 4.16 Proportional Limit and Modulus of Elasticity of Polymers in PSI (cont.)

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
1100-0[7,8]	43.5 (RT)	57 (75°K)	NO DATA	NO DATA
1100-H12[7,8]	23.5 (RT)	46 (75°K)	NO DATA	NO DATA
1100-H14[7]	20 (RT)	42 (75°K)	NO DATA	NO DATA
1100-H16[7,8]	23 (RT)	40 (75°K)	NO DATA	NO DATA
1100-H18[7,8]	16 (RT)	35 (75°K)	NO DATA	NO DATA
2011-T3[7], bar	16 (RT)	26 (75°K)	NO DATA	NO DATA
2011-T8[7], bar	14 (RT)	15 (75°K)	NO DATA	NO DATA
2014-0[7], bar, rolled, drawn	27 (RT)	36 (75°K)	NO DATA	NO DATA
2014-T4[7], bar, rolled, drawn	25 (RT)	27 (75°K)	NO DATA	NO DATA
2014-T6[5,7], bar forged	12.5 (RT)	7 (20°K)	24 (RT)	22 (20°K)
2014-T651[8], plate, longitudinal	10.5 (RT)	12.5 (4.2°K)	24 (RT)	19 (4.2°K)
2014-T651[8], plate, transverse	8 (RT)	10 (4.2°K)	16 (RT)	12 (4.2°K)
2017-T4[7], bar	25 (RT)	28 (75°K)	NO DATA	NO DATA
2018-T61[7], bar	12 (RT)	14 (75°K)	NO DATA	NO DATA

Table 4.17 Percentage Elongation and Percentage Reduction in Area of Aluminum Alloys

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
2020-T6[8], bar	10 (RT)	11 (20°K)	16.5 (RT)	9.5 (20°K)
2020-T6[8], sheet	8 (RT)	11 (20°K)	NO DATA	NO DATA
2021-T81[8]	9 (RT)	11 (20°K)	NO DATA	NO DATA
2024-0[7], bar	22 (RT)	30 (75°K)	NO DATA	NO DATA
2024-T3[7], bar	18 (RT)	22 (20°K)	NO DATA	NO DATA
2024-T3[5], sheet, longitudinal and transverse	18 (RT)	17.5 (20°K)	NO DATA	NO DATA
2024-T4[5,7,8,17], bar	20.5 (RT)	18 (20°K)	28 (RT)	19 (20°K)
2024-T6[8]	11 (RT)	16 (20°K)	NO DATA	NO DATA
2024-T851[8], plate longitudinal	8 (RT)	10 (4.2°K)	17 (RT)	8 (4.2°K)
2025-T6[7]	7 (RT)	12 (20°K)	NO DATA	NO DATA
2218-T61[7], bar	14 (RT)	20 (75°K)	NO DATA	NO DATA
2219-T6[8]	12 (RT)	17 (20°K)	NO DATA	NO DATA
2219-T62[5,8], sheet, longitudinal	11 (RT)	14.5 (20°K)	NO DATA	NO DATA

Table 4.17 Percentage Elongation and Percentage Reduction in Area of Aluminum Alloys (cont.)

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
2219-T62[5,8], sheet, transverse	12 (RT)	16 (20°K)	NO DATA	NO DATA
2219-T81[8], sheet, longitudinal	12 (RT)	13.5 (20°K)	NO DATA	NO DATA
2219-T81[8], sheet, transverse	11 (RT)	15 (20°K)	NO DATA	NO DATA
2219-T87[8], sheet, longitudinal	9 (RT)	13 (20°K)	NO DATA	NO DATA
2219-T87[8], sheet, transverse	8 (RT)	13 (20°K)	NO DATA	NO DATA
2219-T87[8], plate, longitudinal	11 (RT)	12 (20°K)	28 (RT)	27 (20°K)
2219-T87[8], plate, transverse	10 (RT)	13 (20°K)	22 (RT)	23 (20°K)
2618-T6[8], sheet, longitudinal and transverse	7 (RT)	17 (20°K)	NO DATA	NO DATA
2618-T62[8], sheet, longitudinal and transverse	6.75 (RT)	17.5 (20°K)	NO DATA	NO DATA
2618-T651[8], plate, longitudinal	11 (RT)	15 (4.2°K)	32 (RT)	22 (4.2°K)

Table 4.17 Percentage Elongation and Percentage Reduction in Area of Aluminum Alloys (cont.)

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
3003-0[7,8], bar	42 (RT)	47.5 (75°K)	82 (RT)	76 (75°K)
3003-F[7], plate	34 (RT)	42 (75°K)	NO DATA	NO DATA
3003-H12[7,8], bar	23 (RT)	40 (75°K)	NO DATA	NO DATA
3003-H14[8], bar	17 (RT)	32 (4.2°K)	68 (RT)	49 (4.2°K)
3003-H18[7,8], bar	10.5 (RT)	27.5 (75°K)	34 (RT)	46 (75°K)
3004-0[7], bar	26 (RT)	40 (75°K)	NO DATA	NO DATA
3004-F[7], plate	22 (RT)	33 (75°K)	NO DATA	NO DATA
3004-H38[8], bar	13 (RT)	23 (75°K)	NO DATA	NO DATA
4032-T6[7]	10 (RT)	12 (75°K)	NO DATA	NO DATA
5050-0[7], bar	35 (RT)	46 (75°K)	NO DATA	NO DATA
5050-H38[7], bar	15 (RT)	26 (75°K)	NO DATA	NO DATA
5050-T34[7], bar	18 (RT)	30 (75°K)	NO DATA	NO DATA
5052-0[7], bar	29 (RT)	60 (20°K)	NO DATA	NO DATA
5052-F[7], plate	30 (RT)	48 (75°K)	NO DATA	NO DATA
5052-H32[7], bar	22 (RT)	38 (75°K)	NO DATA	NO DATA
5052-H34[7,17], bar	10 (RT)	42 (20°K)	NO DATA	NO DATA

Table 4.17 Percentage Elongation and Percentage Reduction in Area of Aluminum Alloys (cont.)

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
5052-H38[7], bar	17 (RT)	32 (75°K)	NO DATA	NO DATA
5052-H38[5,8], sheet, longitudinal	8 (RT)	31.5 (20°K)	NO DATA	NO DATA
5052-H38[5,8], sheet, transverse	10 (RT)	39.5 (20°K)	NO DATA	NO DATA
5054-H38[5], sheet, longitudinal	9 (RT)	35 (20°K)	NO DATA	NO DATA
5054-H38[5], sheet, transverse	14 (RT)	38 (20°K)	NO DATA	NO DATA
5056-0[7], bar	35 (RT)	50 (75°K)	NO DATA	NO DATA
5056-H34[7], bar	18 (RT)	30 (75°K)	NO DATA	NO DATA
5056-H38[7], bar	15 (RT)	28 (75°K)	NO DATA	NO DATA
5083-0[7,8], bar	23 (RT)	34 (4.2°K)	NO DATA	NO DATA
5083-0[24], plate	20 (RT)	32 (20°K)	25 (RT)	23 (20°K)
5083-H39[8], sheet, longitudinal	6 (RT)	8 (20°K)	NO DATA	NO DATA
5083-H39[8], sheet, transverse	7.5 (RT)	7 (20°K)	NO DATA	NO DATA
5083-H113[7,8], bar	16.5 (RT)	30 (4.2°K)	NO DATA	NO DATA

Table 4.17 Percentage Elongation and Percentage Reduction in Area of Aluminum Alloys (cont.)

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
5083-H113[24], plate	16 (RT)	30 (20°K)	22 (RT)	23 (20°K)
5083-H321[8], plate	15 (RT)	29 (4.2°K)	22 (RT)	33 (4.2°K)
5086-0[7,8,19], bar	24 (RT)	39 (20°K)	NO DATA	NO DATA
5086-0[24], plate	25 (RT)	40 (20°K)	41 (RT)	32 (20°K)
5086-H32[7], bar	16 (RT)	30 (75°K)	NO DATA	NO DATA
5086-H34[5,8], sheet, longitudinal	10 (RT)	30 (20°K)	18 (RT)	25 (20°K)
5086-H34[5,8], sheet, transverse	15 (RT)	25 (20°K)	NO DATA	NO DATA
5086-H112[7], bar	14 (RT)	22 (75°K)	NO DATA	NO DATA
5154-0[7], bar	27 (RT)	52 (20°K)	NO DATA	NO DATA
5154-H32[7], bar	12 (RT)	33 (75°K)	NO DATA	NO DATA
5154-H34[7], bar	17 (RT)	22 (75°K)	NO DATA	NO DATA
5154-H38[5,8], sheet, longitudinal	9.5 (RT)	35 (20°K)	NO DATA	NO DATA
5154-H38[5,8], sheet, transverse	11.5 (RT)	38 (20°K)	NO DATA	NO DATA
5154-H38[7], bar	14 (RT)	25 (75°K)	NO DATA	NO DATA

Table 4.17 Percentage Elongation and Percentage Reduction in Area of Aluminum Alloys (cont.)

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
5356-0[7], bar	30 (RT)	47 (75°K)	NO DATA	NO DATA
5356-H32[7], bar	23 (RT)	33 (75°K)	NO DATA	NO DATA
5356-H34[7], bar	17 (RT)	28 (75°K)	NO DATA	NO DATA
5456-0[7], bar	20 (RT)	30 (75°K)	NO DATA	NO DATA
5456-0[8,24], plate	20 (RT)	28 (4.2°K)	41 (RT)	34 (4.2°K)
5456-H24[8], sheet, longitudinal	13.5 (RT)	6 (20°K)	NO DATA	NO DATA
5456-H24[8], sheet, transverse	7 (RT)	6 (20°K)	NO DATA	NO DATA
5456-H321[5], sheet, longitudinal	14 (RT)	22 (20°K)	NO DATA	NO DATA
5456-H321[5], sheet, transverse	18 (RT)	15 (20°K)	NO DATA	NO DATA
5456-H321[8,24], plate	13 (RT)	22.5 (4.2°K)	26 (RT)	35 (4.2°K)
5456-H343[8], sheet, longitudinal	8 (RT)	10 (20°K)	NO DATA	NO DATA
5456-H343[8], sheet, transverse	11 (RT)	11 (20°K)	NO DATA	NO DATA
6053-0[7], bar	38 (RT)	52 (75°K)	NO DATA	NO DATA

Table 4.17 Percentage Elongation and Percentage Reduction in Area of Aluminum Alloys (cont.)

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
6053-T4[7], bar	30 (RT)	38 (75°K)	NO DATA	NO DATA
6053-T6[7], bar	22 (RT)	30 (75°K)	NO DATA	NO DATA
6061-0[7], bar	32 (RT)	52 (20°K)	NO DATA	NO DATA
6061-T4[7], bar	28 (RT)	33 (75°K)	NO DATA	NO DATA
6061-T4[5], sheet, longitudinal	17 (RT)	31 (20°K)	NO DATA	NO DATA
6061-T4[5], sheet, transverse	17 (17)	34 (20°K)	NO DATA	NO DATA
6061-T6[5,7,8], sheet, longitudinal	14.5 (RT)	24 (20°K)	NO DATA	NO DATA
6061-T6[5,7,8], sheet, transverse	12 (RT)	20 (20°K)	NO DATA	NO DATA
6061-T6[5], bar, forged	20 (RT)	27 (20°K)	53 (RT)	44 (20°K)
6061-T651[8], plate, longitudinal	NO DATA	NO DATA	50 (RT)	42 (4.2°K)
6061-T651[8], plate, transverse	NO DATA	NO DATA	42 (RT)	34 (4.2°K)
6063-0[7], bar, extruded	38 (RT)	NO DATA	NO DATA	NO DATA

Table 4.17 Percentage Elongation and Percentage Reduction in Area of Aluminum Alloys (cont.)

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
6063-T5[7], bar, extruded	20 (RT)	28 (75°K)	NO DATA	NO DATA
6063-T42[7], bar, extruded	33 (RT)	43 (75°K)	NO DATA	NO DATA
6151-T6[7], bar, forged	15 (RT)	18 (75°K)	NO DATA	NO DATA
7002-T6[8], sheet, transverse	11 (RT)	16 (20°K)	NO DATA	NO DATA
7002-T6[8], plate, longitudinal	14 (RT)	18 (20°K)	34 (RT)	20 (20°K)
7002-T6[8], plate, transverse	11 (RT)	17 (20°K)	30 (RT)	13 (20°K)
7039-T6[8]	12 (RT)	18 (20°K)	NO DATA	NO DATA
7039-T61[8], plate, transverse	13 (RT)	16 (20°K)	NO DATA	NO DATA
7075-0[8], bar	17.5 (RT)	21 (75°K)	NO DATA	NO DATA
7075-T6[5,7,8], sheet, longitudinal	11 (RT)	9.5 (20°K)	NO DATA	NO DATA
7075-T6[5,7,8], sheet, transverse	11.5 (RT)	9 (20°K)	NO DATA	NO DATA

Table 4.17 Percentage Elongation and Percentage Reduction in Area of Aluminum Alloys (cont.)

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
7075-T6[5], plate longitudinal	14 (RT)	6 (20°K)	13 (RT)	18 (20°K)
7075-T6[5], plate, transverse	11 (RT)	NO DATA	43 (RT)	NO DATA
7075-T6[5,7,8], bar, rolled	14.5 (RT)	12.5 (20°K)	34.5 (RT)	22 (20°K)
7079-T6[5,8], sheet, longitudinal	12 (RT)	12 (20°K)	NO DATA	NO DATA
7079-T6[5,8], sheet, transverse	11.5 (RT)	9.5 (20°K)	NO DATA	NO DATA
7079-T6[5,8], 5 inch, billet, longitudinal	9.5 (RT)	2.5 (20°K)	18.5 (RT)	4.5 (20°K)
7079-T6[5,8], 5 inch, billet, transverse	7.5 (RT)	1.5 (20°K)	10 (RT)	1 (20°K)
7178-T6[5,8], sheet, longitudinal	12 (RT)	5 (20°K)	NO DATA	NO DATA
7178-T6[5,8], sheet, transverse	12 (RT)	3 (20°K)	NO DATA	NO DATA
7275-T6[5,17], sheet, longitudinal	14 (RT)	5 (20°K)	NO DATA	NO DATA
7275-T6[5,17], sheet, transverse	14 (RT)	4 (20°K)	NO DATA	NO DATA

Table 4.17 Percentage Elongation and Percentage Reduction in Area of Aluminum Alloys (cont.)

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
43[7], sand cast	13 (RT)	8 (75°K)	NO DATA	NO DATA
142-T77[7], sand cast	2 (RT)	2 (75°K)	NO DATA	No DATA
354-T62[25], plate, permanent mold cast	1.1 (RT)	8 (20°K)	3 (RT)	1 (20°K)
355-T6[5,8], sand cast	4 (RT)	2 (20°K)	4 (RT)	20 (20°K)
355-T6[5], bar, permanent mold cast	3 (RT)	2 (20°K)	5 (RT)	2 (20°K)
355-T7[7], sand cast	2.3 (RT)	2 (75°K)	NO DATA	NO DATA
355-T51[7], sand cast	2 (RT)	1 (75°K)	NO DATA	NO DATA
355-T61[5,8], permanent mold cast	5 (RT)	2 (20°K)	6 (RT)	3 (20°K)
356-T6[8], permanent mold cast	12 (RT)	9 (20°K)	14 (RT)	9 (20°K)
356-T7[7], sand cast	3.5 (RT)	3 (75°K)		
356-T61[8], cast	9 (RT)	7 (20°K)	10 (RT)	9 (20°K)
356-T62[25], plate permanent mold cast	2.1 (RT)	3.5 (20°K)	6 (RT)	3 (20°K)
TENS-50-T6[8], sand cast	4.4 (RT)	2.8 (20°K)	9.4 (RT)	4.8 (20°K)
B218-F[25], plate, sand cast	12.9 (RT)	0.8 (20°K)	13 (RT)	1 (20°K)

Table 4.17 Percentage Elongation and Percentage Reduction in Area of Aluminum Alloys (cont.)

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
<u>PURE COPPER</u>				
Pure Copper[22] annealed	47.5 (RT)	63 (4.2°K)	79 (RT)	65 (4.2°K)
Pure Copper[22] 26% cold drawn	17 (RT)	41 (4.2°K)	NO DATA	NO DATA
Pure Copper[22], aged	NO DATA	NO DATA	79 (RT)	73 (4.2°K)
OFHC[8], annealed	18 (RT)	40 (20°K)	76 (RT)	75 (4.2°K)
OFHC[7], cold drawn, hard	18 (RT)	55 (20°K)	NO DATA	NO DATA
<u>COPPER ZINC ALLOYS (BRASSES)</u>				
Commercial Bronze[8,22], bar, 90Cu, 10Zn, annealed	56.5 (RT)	91 (4.2°K)	81 (RT)	73 (4.2°K)
Red Brass[8], bar 84.7Cu, 15.3An, 14% cold red	47 (RT)	82 (4.2°K)	80 (RT)	72 (4.2°K)
Admiralty Brass[8], bar, 72.5Cu, 275Zn, annealed	85 (RT)	93 (4.2°K)	80 (RT)	72 (4.2°K)

Table 4.18 Percentage Elongation and Percentage Reduction in Area of Copper and Copper Alloys

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
70/30 Brass[8,22], bar, 3/4 hard	14 (RT)	32 (20°K)	58 (RT)	58 (20°K)
Yellow Brass[7] 67Cu, 33Zn, 40% cold red	7 (RT)	10 (90°K)	NO DATA	NO DATA
Naval Brass[7], 60Cu, 39Zn, 1 Sn, rolled	47 (RT)	47 (90°K)	NO DATA	NO DATA
Naval Brass[8], bar 61Cu, 39Zn, annealed	37 (RT)	40 (4.2°K)	52 (RT)	48 (4.2°K)
<u>COPPER-TIN ALLOYS (BRONZE)</u>				
Phosphor Bronze A[8,22] 95Cu, 5Sn, 85%, cold drawn	18 (RT)	35 (4.2°K)	78 (RT)	58.5 (4.2°K)
<u>COPPER-SILICON ALLOYS</u>				
Fe-Si Bronze[5], bar	NO DATA	38 (20°K)	NO DATA	40 (20°K)
Silicon Bronze A[8], bar, annealed	66 (RT)	71 (4.2°K)	80 (RT)	69 (4.2°K)
Silicon Bronze[22], 97Cu, 3Si, annealed	65 (RT)	73 (4.2°K)	72 (RT)	70 (4.2°K)

Table 4.18 Percentage Elongation and Percentage Reduction in Area of Copper and Copper Alloys (cont.)

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
Cu-2Ni-1Si, aged	27 (RT)	37 (4.2°K)	58 (RT)	66 (4.2°K)
COPPER-NICKEL ALLOYS				
Copper-Nickel 10[8,22], bar, annealed	37 (RT)	52 (4.2°K)	80 (RT)	72.5 (4.2°K)
Copper-Nickel 30[8,22], bar, annealed	45 (RT)	46.5 (4.2°K)	69 (RT)	65.5 (4.2°K)
COPPER-BERYLLIUM ALLOYS				
Berylco-10[5], bar	15 (RT)	24 (20°K)	34 (RT)	42 (20°K)
Berylco-25[5], bar	10 (RT)	14 (77.6°K)	12 (RT)	22 (77.6°K)
97.7Cu,2Be,0.3Co[7], wrought, soln treated	55 (RT)	50 (90°K)	NO DATA	NO DATA
97.7Cu,2Be,0.3Co[7], wrought, soln treated, age hardened	7 (RT)	10 (90°K)	NO DATA	NO DATA
97.7Cu,2Be,0.3Co[7], wrought, soln treated, 1/2H, age hardened	5 (RT)	6 (90°K)	NO DATA	NO DATA
Beryllium Copper[8], sheet, 1/2 hard	15 (RT)	44 (20°K)	NO DATA	NO DATA

Table 4.18 Percentage Elongation and Percentage Reduction in Area of Copper and Copper Alloys (cont.)

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
97.8Cu,2.6Co,0.6Be[7], wrought, cold drawn 1/2 hard	10 (RT)	49 (20°K)	NO DATA	NO DATA
97.4Cu,2Be,0.6Co[7], cast, soln treaeed, age hardened	1 (RT)	2 (90°K)	NO DATA	NO DATA
Beryllium Copper A[8], bar	62 (RT)	70 (20°K)	80 (RT)	70 (20°K)
Beryllium Copper H[8], bar	20 (RT)	31 (20°K)	NO DATA	NO DATA
97.3Cu,2.3Co,0.4Be[7], cast, soln treated, age hardened	10 (RT)	15 (90°K)	NO DATA	NO DATA
96.8Cu,2.6Co,0.6Be[7], wrought, cold drawn, 1/2 H, age hardened	12 (RT)	16 (90°K)	NO DATA	NO DATA
98Cu,1.1Be,0.9Zn[7], 1/4 H, age hardened	18 (RT)	25 (90°K)	NO DATA	NO DATA
OTHER COPPER ALLOYS				
Aluminum Bronze[8,22], Cu-7Al-2Fe, annealed	43 (RT)	53 (4.2°K)	62 (RT)	59 (4.2°K)
Cu-10Al-5Ni-3Fe[8,22] cast	12 (RT)	7 (4.2°K)	9 (RT)	5 (4.2°K)

Table 4.18 Percentage Elongation and Percentage Reduction in Area of Copper and Copper Alloys (cont.)

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
99.85% Pure Nickel[7,8], annealed	47 (RT)	62 (4.2°K)	80 (RT)	72 (20°K)
Commercially Pure Ni[7], as forged	121 (RT)	22 (20°K)	NO DATA	NO DATA
Hastelloy B[8], sheet, 20% cold red	34 (RT)	47 (20°K)	NO DATA	NO DATA
Hastelloy B[8], sheet 40% cold red	8 (RT)	22 (20°K)	NO DATA	NO DATA
Hastelloy C[8], sheet, soln treated	48 (RT)	50 (20°K)	57 (RT)	36 (20°K)
Hastelloy C[8], sheet, 20% cold red, longitudinal	13 (RT)	32 (20°K)	NO DATA	NO DATA
Inconel[7], 10% cold drawn	42 (RT)	50 (20°K)	NO DATA	NO DATA
Inconel[8], bar 20% cold red	18 (RT)	32 (20°K)	58 (RT)	55 (20°K)
Inconel X[5], sheet, annealed, longitudinal, transverse	25 (RT)	30.5 (20°K)	NO DATA	NO DATA
Inconel X[5], bar	25 (RT)	14 (20°K)	28 (RT)	14 (20°K)

Table 4.19 Percentage Elongation and Percentage Reduction in Area of Nickel and Nickel Alloys

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
Inconel X[8], soln treated and aged	10 (RT)	27 (20°K)	28 (RT)	15 (20°K)
Inconel 718[8], soln treated and aged	10 (RT)	18 (20°K)	35 (RT)	35 (20°K)
Inconel 718[8], cold reduced and aged	10 (RT)	18 (20°K)	NO DATA	NO DATA
Monel[7], as forged	33 (RT)	38 (20°K)	NO DATA	NO DATA
K-Monel[5], sheet, age hardened	22 (RT)	28 (20°K)	NO DATA	NO DATA
K-Monel[8], cold drawn 45%	32 (RT)	35 (20°K)	NO DATA	NO DATA
K-Monel[8], sheet, soln treated and aged	23 (RT)	30 (20°K)	52 (RT)	52 (20°K)
S-Monel[8], cast, annealed	7 (RT)	15 (20°K)	31 (RT)	24 (20°K)
Nickel-Chromium[7] Resistance Alloy	28 (RT)	35 (20°K)	NO DATA	NO DATA
Nickel Iron Alloy	30 (RT)	19 (20°K)	NO DATA	NO DATA
René 41[5], sheet, age hardened, longitudinal	18 (RT)	6 (20°K)	NO DATA	NO DATA

Table 4.19 Percentage Elongation and Percentage Reduction in Area of Nickel and Nickel Alloys (cont.)

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
René 41[5], sheet age hardened, transverse	12 (RT)	5 (20°K)	NO DATA	NO DATA
René 41[8], soln treated and aged	29 (RT)	23 (20°K)	33 (RT)	25 (20°K)
Waspaloy[5], bar	28 (RT)	18 (20°K)	28 (RT)	14 (20°K)
Al-718[6], forging, annealed	17 (RT)	13 (20°K)	NO DATA	NO DATA
Al-718[6], cold rolled strip	20 (RT)	9 (20°K)	NO DATA	NO DATA
D-979[8], sheet, annealed	30 (RT)	20 (20°K)	NO DATA	NO DATA
L-605[8], sheet, 20% cold red	17 (RT)	19 (20°K)	NO DATA	NO DATA
L-605[8], sheet 40% cold red	3 (RT)	1 (20°K)	NO DATA	NO DATA
L-605[8], sheet, annealed	46 (RT)	27 (20°K)	NO DATA	NO DATA
R-235[8], sheet, soln treated, longitudinal	28 (RT)	34 (20°K)	NO DATA	NO DATA

Table 4.19 Percentage Elongation and Percentage Reduction in Area of Nickel and Nickel Alloys (cont.)

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
R-235[8], sheet soln treated, longitudinal	28 (RT)	34 (20°K)	NO DATA	NO DATA
R-235[8], sheet soln treated, transverse	33 (RT)	35 (20°K)	NO DATA	No DATA

Table 4.19 Percentage Elongation and Percentage Reduction in Area of Nickel and Nickel Alloys (cont.)

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
IRON AND IRON ALLOYS				
Iron Ingot[7], hot rolled	28 (RT)	0 (4.2°K)	NO DATA	NO DATA
Invar[8], bar, 12-15% cold red	21 (RT)	22 (20°K)	62 (RT)	57 (20°K)
Ni-Span-C[8], bar, soln treated and aged	24 (RT)	30 (20°K)	50 (RT)	43 (20°K)
CONSTRUCTION STEELS				
AISI/SAE 1043[21], plate, longitudinal	28 (RT)	0 (20°K)	NO DATA	NO DATA
AISI/SAE 1043[21], plate, transverse	20 (RT)	1 (20°K)	NO DATA	NO DATA
AISI/SAE 1075[8], bar, quenched and tempered	18 (RT)	2 (20°K)	58 (RT)	6 (20°K)
AISI/SAE 4340[8], bar, hardened and tempered	17 (RT)	3 (4.2°K)	51 (RT)	11 (4.2°K)
Nickel Alloy Steel[7], 2% Ni, 0.12% C, annealed	20 (RT)	0 (20°K)	NO DATA	NO DATA

Table 4.20 Percentage Elongation and Percentage Reduction in Area of Ferrous Materials

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
2800 (9% Ni)[8], bar, double normalized, stress relieved	24 (RT)	18 (20°K)	70 (RT)	47 (20°K)
18% Ni Maraging Steel[8], sheet, 250 grade, soln treated	7.5 (RT)	5 (20°K)	NO DATA	NO DATA
18% Ni Maraging Steel[8], sheet, 250 grade, soln treated	3.3 (RT)	1.5 (20°K)	NO DATA	NO DATA
H-11 (5% Cr) Steel[8], bar	11 (RT)	1 (20°K)	38 (RT)	0 (20°K)
STAINLESS STEELS - MARTENSITIC				
AISI 410[8], bar, hardened and tempered	14 (RT)	1 (20°K)	70 (RT)	5 (20°K)
AISI 416[8], bar quenched and tempered	15 (RT)	0 (20°K)	53 (RT)	2 (20°K)
17-4PH-H1100[8], bar	16 (RT)	1 (20°K)	58 (RT)	5 (20°K)
STAINLESS STEEL - AUSTENITIC				
AISI 202[5], bar, annealed	85 (RT)	12 (20°K)	NO DATA	NO DATA

Table 4.20 Percentage Elongation and Percentage Reduction in Area of Ferrous Materials (cont.)

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
AISI 301[8], plate, annealed	NO DATA	NO DATA	68 (RT)	48 (4.2°K)
AISI 301[5,8], sheet, 3/4 hard	17 (RT)	14 (20°K)	NO DATA	NO DATA
AISI 301[5,8], sheet, full hard	6 (RT)	15 (20°K)	NO DATA	NO DATA
AISI 301[5,8], sheet, extra hard, cold rolled	10.5 (RT)	12 (20°K)	NO DATA	NO DATA
AISI 301[8], extra full hard	13 (RT)	21 (20°K)	NO DATA	NO DATA
AISI 301N[11], 60% cold rolled	12 (RT)	12 (20°K)	NO DATA	NO DATA
AISI 301N[5], sheet, extra full hard, longitudinal	16 (RT)	9 (20°K)	NO DATA	NO DATA
AISI 301N[5], sheet, extra full hard, transverse	11 (RT)	4 (20°K)	NO DATA	NO DATA
AISI302[5,7,11], annealed	72.5 (RT)	25 (20°K)	80 (RT)	55 (20°K)

Table 4.20 Percentage Elongation and Percentage Reduction in Area of Ferrous Materials (cont.)

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
AISI 302 (5,8), sheet, 40% cold rolled, longitudinal	7.5 (RT)	29.5 (20°K)	NO DATA	NO DATA
AISI 302 (5,8), sheet, 40% cold rolled transverse	NO DATA	16 (20°K)	NO DATA	NO DATA
AISI 302 (5,8), sheet, 60% cold rolled, longitudinal	3 (RT)	19.5 (20°K)	NO DATA	NO DATA
AISI 302 (5,8), sheet, 60% cold rolled, transverse	NO DATA	7 (20°K)	NO DATA	NO DATA
AISI 302 (8), bar	NO DATA	NO DATA	61 (RT)	35 (4.2°K)
AISI 302 (8), bar, cold reduced	NO DATA	NO DATA	76 (RT)	36 (20°K)
AISI 303 (5,8), bar, annealed	60 (RT)	30 (4.2°K)	65 (RT)	36 (4.2°K)
AISI 303 (7), 10% cold drawn	65 (RT)	30 (20°K)	NO DATA	NO DATA
AISI 304 (5,7), bar, annealed	78 (RT)	39 (20°K)	NO DATA	NO DATA
AISI 304 (6), plate	60 (RT)	50 (20°K)	NO DATA	NO DATA

Table 4.20 Percentage Elongation and Percentage Reduction in Area of Ferrous Materials (cont.)

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
AISI 304[8]	37 (RT)	20 (20°K)	38 (RT)	20 (20°K)
AISI 304L[5], bar, annealed	60 (RT)	41 (20°K)	60 (RT)	57 (20°K)
AISI 304L[11], 50% cold rolled	6 (RT)	1 (20°K)	NO DATA	NO DATA
AISI 304L[6], cold rolled, full hard	6 (RT)	1 (20°K)	NO DATA	NO DATA
AISI 308[8], 15% cold drawn	70 (RT)	40 (20°K)	NO DATA	NO DATA
AISI 310[5,8,11], bar, annealed	60 (RT)	56 (20°K)	67 (RT)	45 (20°K)
AISI 310[5,8], sheet, 40% cold rolled, longitudinal	3.5 (RT)	28 (20°K)	NO DATA	NO DATA
AISI 310[5,8], sheet, 40% cold rolled, transverse	3 (RT)	25 (20°K)	NO DATA	NO DATA
AISI 310[5,8], sheet, 60% cold rolled, longitudinal	3 (RT)	18 (20°K)	NO DATA	NO DATA
AISI 310[5,8], sheet, 60% cold rolled, transverse	NO DATA	16 (20°K)	NO DATA	NO DATA

Table 4.20 Percentage Elongation and Percentage Reduction in Area of Ferrous Materials (cont.)

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in Area (upper temp)	% Red. in Area (lowest temp)
AISI 310 (5,8), sheet, 75% cold rolled, longitudinal	3 (RT)	13 (20°K)	NO DATA	NO DATA
AISI 310 (5,8), sheet, 75% cold rolled, transverse	NO DATA	2 (20°K)	NO DATA	NO DATA
AISI 310 (6), cold rolled, extra hard	3 (RT)	14 (20°K)	NO DATA	NO DATA
AISI 310 (6,7), plate	60 (RT)	55 (20°K)	NO DATA	NO DATA
AISI 316 (5,6,7,8), annealed	70 (RT)	55 (20°K)	77 (RT)	60 (20°K)
AISI 316 (7), 25% cold drawn	35 (RT)	30 (20°K)	NO DATA	NO DATA
AISI 321 (7,8), bar, annealed	57 (RT)	35 (20°K)	80 (RT)	43 (20°K)
AISI 347 (5,8) annealed	52 (RT)	35 (20°K)	71 (RT)	53 (20°K)
AISI 347 (5,7), bar, annealed	50 (RT)	41 (20°K)	60 (RT)	50 (20°K)
AISI 347 (7), 10% cold drawn	47 (RT)	37 (20°K)	NO DATA	NO DATA

Table 4.20 Percentage Elongation and Percentage Reduction in Area of Ferrous Materials (cont.)

MATERIAL	% Elongation (upper temp)	% Elongation (lowest temp)	% Red. in ARea (upper temp)	% Red. in Area (lowest temp)
A-286[6,8], cold rolled, strip, aged	17 (RT)	24 (20°K)	NO DATA	NO DATA
A-286[8], soln treated, longitudinal	20 (RT)	30 (20°K)	49 (RT)	41 (20°K)
A-286[8], soln treated, transverse	30 (RT)	35 (20°K)	NO DATA	NO DATA
AM-350[5], bar, annealed	40 (RT)	7 (20°K)	NO DATA	NO DATA
AM-350[7], sheet, tempered	13 (RT)	0 (20°K)	NO DATA	NO DATA
AM-350-H[8], bar, annealed	40 (RT)	7 (20°K)	NO DATA	NO DATA
AM-355[8], sheet, cold rolled, longitudinal	5 (RT)	0 (20°K)	NO DATA	NO DATA
AM-355[8], sheet, cold rolled, transverse	7.5 (RT)	0 (20°K)	NO DATA	NO DATA
Tenelon[8], bar, annealed	80 (RT)	3 (20°K)	NO DATA	NO DATA
17-7PH-TH1050[8], sheet	11 (RT)	0 (20°K)	33 (RT)	0 (20°K)

Table 4.20 Percentage Elongation and Percentage Reduction in Area of Ferrous Materials (cont.)

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